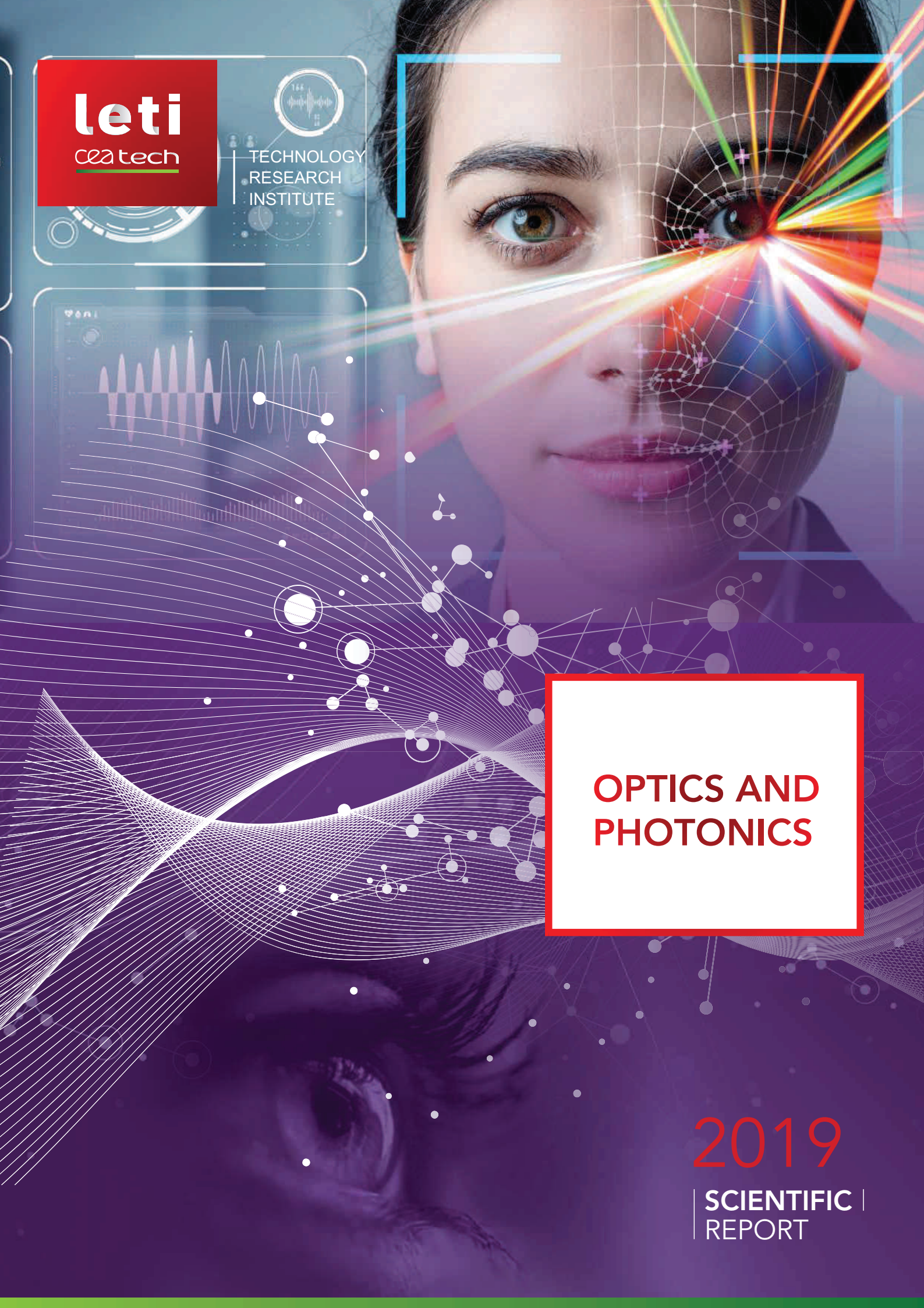




leti
cea tech

TECHNOLOGY
RESEARCH
INSTITUTE

OPTICS AND PHOTONICS

2019

SCIENTIFIC |
REPORT



TECHNOLOGY
RESEARCH
INSTITUTE

COMMITTED TO INNOVATION, CEA-Leti CREATES DIFFERENTIATING SOLUTIONS WITH ITS PARTNERS.

CEA-Leti is a research institute of CEA Tech and a recognized global leader in miniaturization technologies.

CEA-Leti's teams are focused on developing secure solutions that will enable future information and communication technologies, health and wellness approaches, clean and safe energy production and recovery, sustainable transport, space exploration and cybersecurity.

For 50 years, the institute has built long term relationships with its industrial partners, tailoring innovative and differentiating solutions to their needs. Its entrepreneurship

programs have sparked the creation of 65 start-ups.

CEA-Leti and its industrial partners work together through bilateral projects, joint laboratories and collaborative research programs, as illustrated in this report.

CEA-Leti maintains an excellent scientific level by working with the best research teams worldwide, establishing partnerships with major research technology organizations and academic institutions. CEA-Leti is also a member of the French Carnot Institutes network*.

*Carnot Institutes network: French network of 39 institutes serving innovation in industry.



CEA Tech is the technology research branch of the French Alternative Energies and Atomic Energy Commission (CEA), a key player in research, development and innovation in defense & security, nuclear energy, technological research for industry and fundamental physical and life sciences.

www.cea.fr/english

CEA-Leti at a glance

800
publications per year

ISO 9001
certified since 2000

114
European projects

Founded in
1967

Based in
France (Grenoble)
with offices in the

US (San Francisco) and
Japan (Tokyo)

300
industrial partners

1,850
researchers

3,100
patents in portfolio

10,000
sq. meters cleanroom
100-200-300 mm wafers

65
startups created

OPTICS AND PHOTONICS

Within CEA Tech and CEA-Leti, activities of the Optics and Photonics division cover most of the biggest industrial markets for photonics:

- all-wavelength imaging (visible, infrared, THz)
- optical data communications
- optical environmental and 3D sensors
- solid-state lighting
- information displays

The R&D projects are carried out with both industrial and academic partners. The industrial partners of the Optics and Photonics division range from local SMEs to overseas and global companies.

Our projects merge fundamental physical aspects with advanced technological developments, they interweave nano- sciences, optics, micro-electronics, advanced nano-fabrication, integration and packaging, all while taking into account system requirements.





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OPTICS AND PHOTONICS

FOREWORD



Dr. Agnes Arnaud,
Head of the Optics and Photonics Division

For more than 40 years, Optics and Photonics Division of the CEA-Leti assists the high-tech industry by transforming results of advanced research into products.

Photonics is a recognized More-than-Moore technology. Its progress accelerates through integration with electronics at the system level, at the device / package level, and through common fabrication steps in silicon foundries. Today, Leti's organization reflects this shift: all our photonics-oriented clean rooms are seamlessly integrated with Leti's main 200/300 mm microelectronic fabs.

Simultaneously, Leti opens even more to photonic (sub-)systems of higher added value, by embedding photonics-specific microelectronic circuit designer into the "photonic" teams.

Leti is active in most of the biggest photonic markets:

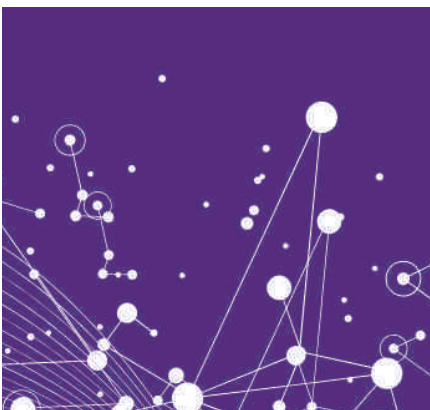
- Imaging, from THz to infrared and to visible,
- Silicon photonics for datacoms and related applications
- Optical environmental sensors
- Information displays

Among our scientific activity this year we can note a strengthening of our industrial collaborations for our historical and mature technologies. But also an extension of our innovations in the fields of photonic applications, such as curved imagers and micro-displays, inorganic micro-displays, lidars and integrated depth sensors, lensless microscopic imaging in the mid-infrared. And finally, we have explored new pathways, such as perovskites for X-ray detection, plenoptic RGB+Z, quantum computing and neuromorphic photonics.

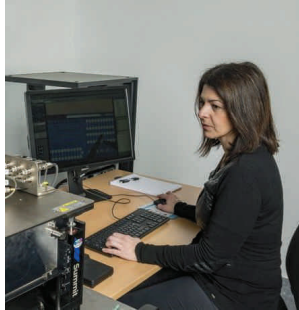
Although the year 2020 is a special year, we look into the future with spirit and optimism, being strong of all our partnerships, of our people and our infrastructures.

We base this annual report on the open publications, which reflect only a subset of our recent results.

Hoping it attracts your interest, I look forward to direct contacts with you.



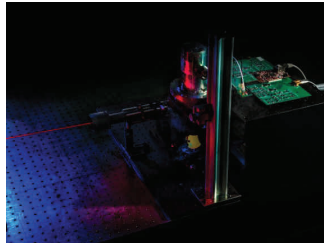
KEY FIGURES



200 permanent R&D engineers and technicians

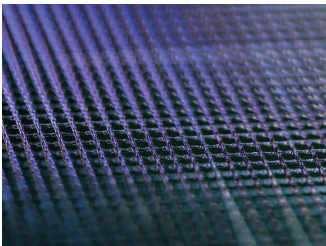
45 PhD students and post-docs

50 "CEA experts"



140 publications in 2019 including

55 papers in peer reviewed journals



75 patents filed in 2018

520 patents in portfolio

20% under licensing contract



Leti's crystal growth and epi facilities,
dedicated II-VI and III-V clean rooms with
versatile substrate geometries up to 150
mm

Leti's 200 mm and 300 mm CMOS clean
rooms with numerous photonic fab
processing modules

Intégration and packaging



Material, optical and opto-electronic
characterization facilities

Advanced means of modeling and simulation

SCIENTIFIC ACTIVITY

Prizes and awards

Best Paper Award at the Photonics West 2019 MOEMS & Miniaturised Systems XVIII session by Jean-Guillaume Coutard for "Photoacoustic cell on silicon for mid-infrared QCL-based spectroscopic analysis"

Contribution to the Best Paper Award at the 69th ECTC Conference by Perceval Coudrain (Leti/DCOS) for "Active Interposer Technology for Chiplet-Based Advanced 3D System Architectures"

"Student Best Paper Runner-up" award at ISCAS'19 by Wissam Benjilali for "An Analog-to-Information VGA Image Sensor Architecture for Support Vector Machine on Compressive Measurements"



Scientific committees

Technical Program committees of: IEEE Photonics Summer Topicals, IWLPC, ECTC

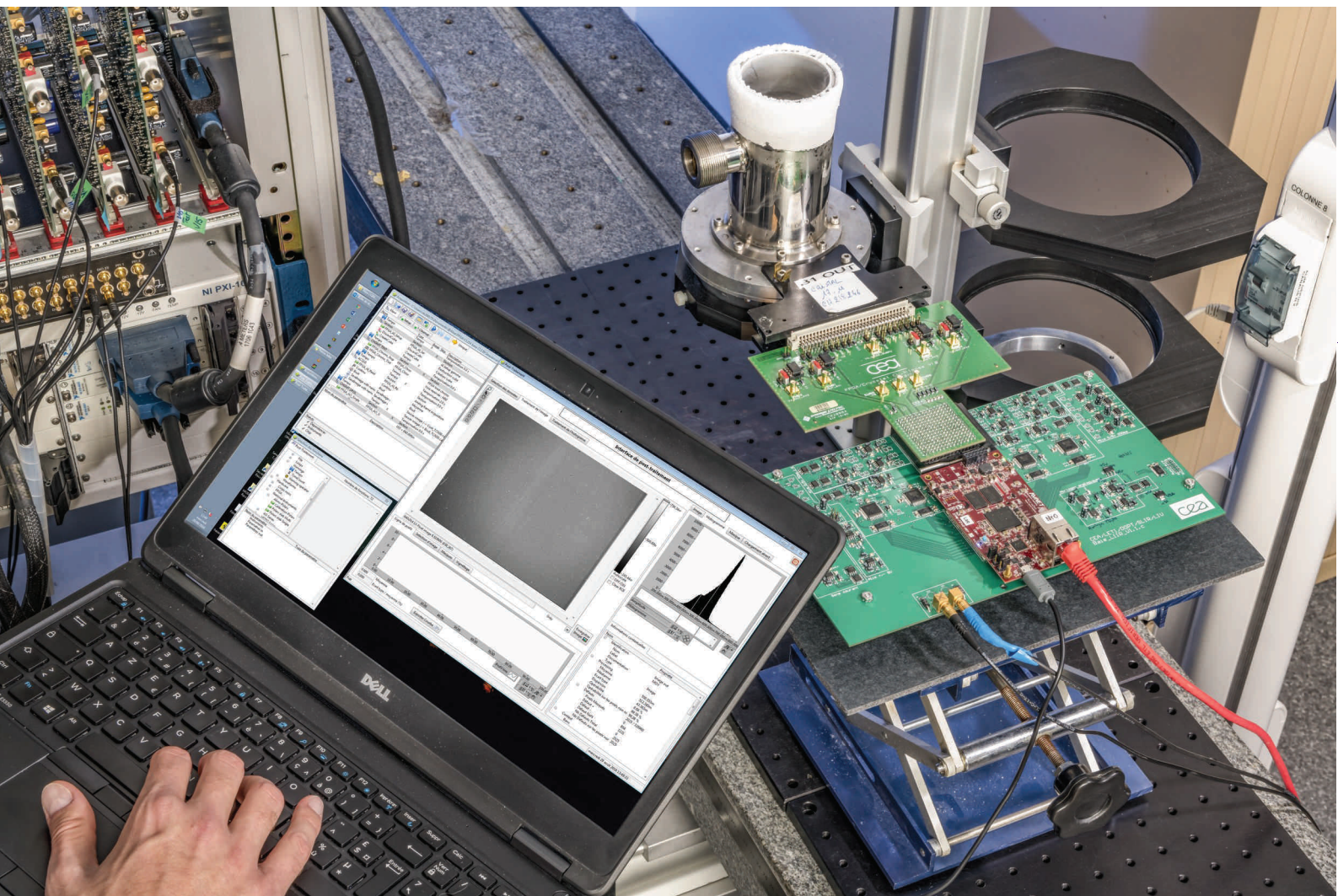


photo credit: Denis Morel

01

IR IMAGING: II-VI COOLED

- **Dark current modeling of HgCdTe diodes**
- **MTF of small pixels with EBIC**
- **High count rate single photon APDs**
- **Small pitch MWIR focal-plane-arrays**
- **Assembly of small-pitch focal-plane-arrays with In microballs**

HgCdTe diode dark current modelling: Rule 07 revisited for LW and VLW

RESEARCH TOPIC:

Low dark currents in HgCdTe devices for infrared detection in astronomical (deep space and earth observations) domain.

AUTHORS:

N. Baier, O. Gravrand, C. Lobre, O. Boulade (IRFU/DAP)
A. Kerlain, N. Péré-Laperne (LYNRED)

Rule 07 is a very convenient way for the dark current estimation of high quality HgCdTe P-on-n photodiodes. Its popularity is due to the fact that it is very easy to use, while giving an accurate description of dark current evolution with both temperature and cutoff. This modeling is actually the result of an empirical fit to experimental data from Teledyne Imaging Systems (TIS). However, at high cutoffs and temperatures lower than 78K, measured dark current deviates from this rule. In this paper, a measured dataset from LETI devices was presented and discussed. Then a new empirical rule describing HgCdTe P-on-N HgCdTe diodes dark current is proposed. This new expression should describe low temperature LWIR and VLWIR dark current more accurately.

SCIENTIFIC COLLABORATIONS: CNES, LabEx FOCUS, ESA

Context and Challenges

Rule07 is a heuristic law proposed in two papers by W. Tennant from Teledyne Imaging Systems (doi.org/10.1007/s11664-008-0426-3 and doi.org/10.1007/s11664-010-1084-9) and serves as a reference for infrared devices. This empirical tool is very convenient to compute the evolution of dark current on 13 orders of magnitude, using only few parameters [1]. However, its simplicity leads users to apply it outside the parameters definition ranges, especially at high cutoff wavelength and low temperature. Moreover, it describes dark current evolution with temperature in a way that is not physically meaningful.

Main Results

The P-on-n photodiodes architecture at CEA-LETI relies on a MCT active base layer grown by liquid phase epitaxy. IRFPAs manufactured with the standard process exhibit state-of-the-art properties [2]. These devices meet the requirements for tactical applications and should fulfil the requirements for astronomical, deep space and earth observations applications. Actually, in these domains, some constraints have a strong impact on the detector performances, requiring low dark current and low operating temperature.

To overcome these issues, the *bandgap widening* process has been developed and tested at DEFIR (joint laboratory between CEA-LETI and Lynred) [3]. It aims at forming a heterojunction so that the junction is placed in a material with higher bandgap than the active layer. The higher the bandgap at the junction is, the lower depletion currents will be. Thus dark current will remain dominated by diffusion current at lower temperature, fulfilling the application requirements.

30 devices have been manufactured, with cutoff wavelengths ranging from 9.5 to 17.2 μm (world premiere with this kind of device) at 78K [4]. The detectors exhibit top end performances, with pixel operability of 99.98%, background limited noise and quantum efficiency up to 90%. Dark current is dominated by diffusion current down to 38K, where it shifts to depletion current.

Rule07 can be used as a comparison tool to evaluate the good

level of dark current. Fig. 1b, it can be seen that at high temperature this law is a good predictor of dark current. But at lower temperature, the dark current is underestimated, while well fitted with physical relations.

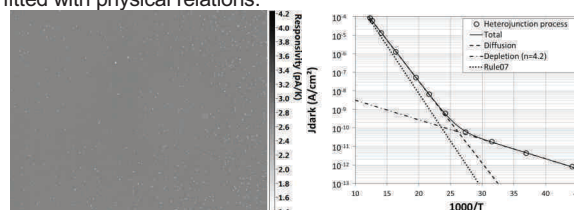


Fig. 1. a) Responsivity mapping of VLWIR FPA (left) and b) dark current evolution with temperature (right).

The dataset from LETI has been used to extract new parameters to revisit and enhance Rule07 [5]. This new law, while still convenient, provides a better descriptor of IR devices dark current for a large range of cutoff wavelengths and temperature.

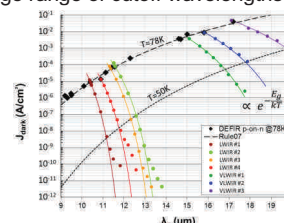


Fig. 2. New empirical law estimation of dark current evolution with temperature for various L-VLWIR cutoff wavelengths.

Perspectives

While providing a more robust tool to evaluate the dark current on a wide range of temperature and cutoff wavelength, LETI demonstrated its ability to manufacture high-end performances devices for high requirement level applications such as astronomical ones.

RELATED PUBLICATIONS:

- [1] O. Gravrand et al, <https://doi.org/10.1007/s11664-009-0795-2>
- [2] L. Mollard et al, <https://doi.org/10.1007/s11664-011-1692-z>
- [3] N. Baier et al, <https://doi.org/10.1007/s11664-015-3851-0>
- [4] N. Baier et al, <https://doi.org/10.1117/12.2016369>
- [5] N. Baier et al, <https://doi.org/10.1007/s11664-019-07299-z>

Modulation Transfer Function characterization of small pixel pitch IR cooled photodiodes using Electron Beam induced current

RESEARCH TOPIC:

Cooled IR imaging; HgCdTe; Small pixel pitch
Modulation Transfer function; Electron Beam Induced Current

AUTHORS:

A. Yèche, O. Gravrand, A. Ferron, F. Boulard, S. Bisotto, F. Rochette, J. Abergel

Experimental assessment of small pitch cooled infrared focal plane arrays (FPA) modulation transfer function (MTF) is becoming an important issue. Indeed, the MTF may be degraded by lateral diffusion in such small pixels. Moreover, the pitch also approaches the sensed wavelength so that direct MTF measurement using optical projections becomes difficult. We propose the use of electron beam induced current (EBIC) to experimentally characterize the MTF of small pitch cooled FPAs. The diode area is scanned by the electron beam from an electron microscope instead of an optical beam in classical MTF measurement. Due to the very narrow electron beam, the MTF can then be estimated with an excellent precision. First scans of mid wave (MW) 7.5 μm pitch HgCdTe diodes demonstrate 55% MTF at Nyquist frequency, which represents a very good performance for such a small pixel pitch.

Classical ways of characterizing MTF involves most of the time the projection of an optical pattern onto the array surface. This pattern can be a scanning point (spotscan experiment), a line (linescan experiment), a Heaviside function (knife-edge experiment) or even complicated patterns exciting different spatial frequencies (Talbot experiment). Whatever the optical system (in far field) and the pattern used, the accessible spatial frequency range is limited by the cutoff of the optics and the bench contribution to MTF (due to diffraction) is not negligible in the result, degrading the measurement precision. For ultimate pixel pitches such as 5 to 3 μm in MW, the Nyquist frequency is almost not accessible using optical means (the pitch is smaller than the Airy pattern size). In this context, EBIC performed at low temperature represents an interesting alternative for the MTF measurement of small pixel pitch flip-chip detectors.

When the rear substrate is removed, the electron beam from the microscope can be scanned through the rear interface of the flip-chip diode array. In fact, the experiment mimics a classical spotscan, using an electron beam excitation instead of the classical photon beam. However, the EBIC configuration is no longer limited by the Airy disc but by the extension of the interaction volume of the electron beam in the narrow gap material. When the substrate is completely removed, the beam energy can be lowered sufficiently to keep the interaction volume in the range of only a few 100 nm, far below the optical diffraction limit. The resulting PSF (Point Spread Function) estimation is then much more accurate, and the corresponding MTF estimation appears free of artefacts due to the bench optics. Fig. 1 shows an example of EBIC scan carried out on flip-chip 7.5 μm pitch MW HgCdTe detector from CEA-LETI. Corresponding MTF is shown in Fig. 2, exhibiting 55% at Nyquist frequency. This value appears consistent with 2D and 3D electro-optical modelling.

In the coming years, this EBIC technic will be compared with other MTF optical characterisations such as spotscan or interferometric methods. This comparison will be carried out in the frame of a PhD at ONERA Palaiseau.

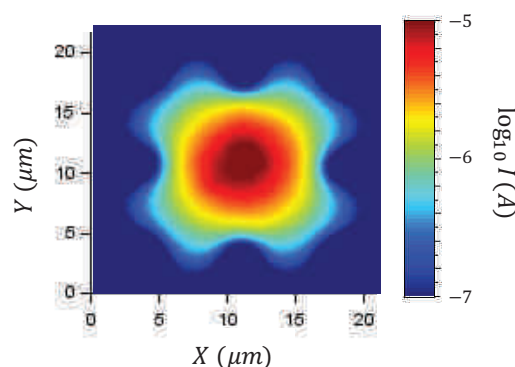


Fig. 1. EBIC scan of a 7.5 μm pitch pixel MW, at 120K

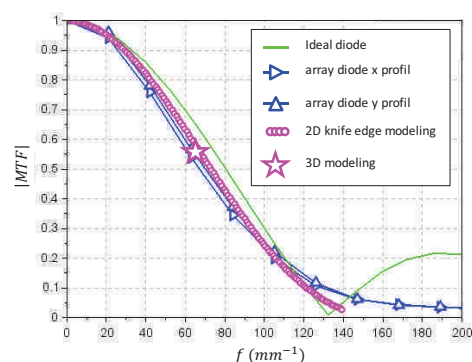


Fig. 2. EBIC MTF estimation from Fig1, compared with TCAD simulations

RELATED PUBLICATIONS:

- [1] A. Yèche, O. Gravrand, A. Ferron, F. Boulard, S. Bisotto, F. Rochette, J. Abergel, "MTF characterization of small pixel pitch IR cooled photodiodes using EBIC", 2019 workshop of ii-vi compounds, Chicago
- [2] A. Yèche, O. Gravrand, A. Ferron, F. Boulard, S. Bisotto, F. Rochette, J. Abergel, J. Electron. Mater. (2020), <https://doi.org/10.1007/s11664-020-08253-0>
- [3] A. Yèche, F. Boulard, O. Gravrand, J. Electron. Mater. (2019) <https://doi.org/10.1007/s11664-019-07140-7>

Efficient single photon detection at high count rates with HgCdTe APD detectors

RESEARCH TOPIC:

Meso-photonic photo-detector development based on HgCdTe APD

AUTHORS:

Johan Rothman, Salvatore Pes, Julie Abergel, Jean-Alain Nicolas; Jean-Pierre Rostaing, Sebsten Renet

A record high single photon detection rate of 500 MHz in free running and linear mode has been demonstrated with a HgCdTe APD detector module developed at CEA/LETI. This performance was reached by the combination of a specifically designed high bandwidth and low noise CMOS amplifier, hybridized with high gain HgCdTe APDs operated in linear mode. The photon detection efficiency jitter were estimated using an original post processing of detected pulses from an attenuated Poisson state with $\mu=1.6$ photons. The corresponding jitter and event detection efficiency were estimated to 277 ps and 87 %, respectively. The results demonstrate the potential of this detector technology for emerging single photon application such as quantum information processing.

SCIENTIFIC COLLABORATIONS: ESA, labex FOCUS, DPFT

Context and Challenges

A new hybrid detector developed have been within the frame of an ESA project to address free space optical communication at high rate, down to single photon sensitivity and low temporal jitter. The development required to push the CMOS technology to its limit in terms of noise and bandwidth to achieve a high sensitivity amplifier to be hybridized with HgCdTe APDs with gain in excess of 100 and a fast response time.

Main Results

The detector module was integrated into a specifically designed LN2 cryostat (80 K) and characterized using a pulsed laser source. The laser has a pulse width of 40 ps and a repetition rate that can be varied between 100 kHz and 1 GHz. The light was strongly attenuated to reach Poisson states with an average photon number μ at single photon levels. Fig. 1a) reports a series of temporal signal obtained for an average state of $\mu=1.6$ photons on the detector obtained with an APD gain of 180. A small pulse is observed at the instant of arrival of the laser pulse (indicated by the dotted line) on the three first traces. The pulse width of 1.2 ns and fall time of 800 ps corresponds to a bandwidth of 430 MHz, mainly limited by the COMS amplifier. The fluctuation in amplitude between the detected events is due to fluctuation in the number of incoming photons and/or to the gain of the APDs. No impulse is observable on the last (black) signal, corresponding to an absence of photons at the input of the detector or a non-detection event of a photon that do not generate a detectable multiplication avalanche.

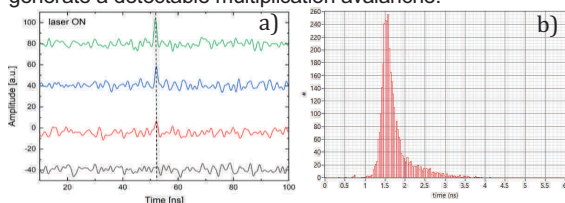


Fig. 1. a) Four signal traces with single photon level pulses and b) the estimated timing jitter.

The detection of single photon in linear mode brings important advantages such as absence of dead time, ultra-low after pulsing and conservation of photon number information. However, the APD gain fluctuations between each event makes their detection more difficult, in particular if the data needs to be processed in real time. At present, we have used an original post-processing that allows us to estimate the detection efficiency, the detected photon distribution and the timing jitter. This procedure was applied on a large data set with $\mu=1.6$ photons and yielded an event detection efficiency of 87 % and a timing jitter of 277 ps (see Fig. 1b)[1].

The capacity to reach high-count rate was qualitatively demonstrated by the observation of well-separated single photon level pulses on the detector. This was observed up to count rates of 500 MHz, as illustrated in Fig 2.

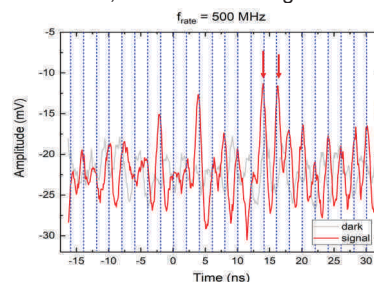


Fig. 1. Signal detected with the HgCdTe APD detector module with a 500 MHz single photon level pulses (red) and without laser (grey)

Perspectives

The combination of high detection efficiency, photon-number resolution, record high count rates at moderate operating temperature are strong assets for the HgCdTe technology to respond to the challenges in emerging quantum optical information processing. In a short time perspective, the detector technology will be optimized through the development of new

RELATED PUBLICATIONS:

[1] Meso-photonic detection with HgCdTe APDs at high-count rates, J. Rothman et. al, accepted for publication in J. Electron. Mater. (2020).

Developments of 7.5 μ m and 5 μ m pitch HgCdTe IRR focal-plane-arrays in mid wave Infrared

RESEARCH TOPIC:

Cooled IR imaging; HgCdTe; Small pixel pitch; ROIC; hybridization; In bumps

AUTHORS:

S.Bisotto, J.Abergel, B.Dupont, A.Ferron, O.Maillart, JA. Nicolas, S.Renet, F.Rochette, JL. Santailier

The pitch reduction in IR systems is a subject of major concern. Numerous papers accurately describe the interest and challenges of the miniaturization of infrared sensor systems, mainly the resolution increase for the same sensor size. Sub 10 μ m pitch IRFPAs are now available in the manufacturers products. Even large arrays of ultra-small pitch have been demonstrated. But to address the very small pitch, many challenges must be overcome. The performance must remain untouched so the modulation transfer function (MTF) as a measure of the blurring of the images has become the new figure of merit besides the noise and thermal sensitivity (NETD).

The CEA-Leti has developed all the steps from the simulation of MTF, the growing of crystals and HgCdTe active layers, the diode process, involving also the read-out-integrated-circuit (ROIC) design and the hybridization process leading to functional 7.5 μ m and 5 μ m FPAs.

Context and Challenges

As MCT remains a material of primary interest for IR detector development at the LETI and LynRed (formerly SOFRADIR) joint laboratory (DEFIR), consistent effort has been applied during the last few years to improve all the steps towards very small pitch focal-plane-arrays (FPAs) achievement, foreseeing the next small pitch generation.

Going to small pitches is challenging in many ways, MCT sensors are very high quality detectors so all the steps are very quality demanding.

To demonstrate the overall feasibility from material to hybridized detector in laboratory conditions, two demonstrators have been achieved and characterized : a 7.5 μ m pitch 640x512 MWIR MCT FPA and a 5 μ m pitch 64x152 MWIR MCT FPA.

Our aim was not only a demonstration but a large parametric study in order to master which step is reachable with our current equipment, and which needed a technological breakthrough for the future.

Main Results

An accurate model for MTF has been developed to foresee the design of the IR FPAs at the beginning of the study and to check with the MTF measurements when the realization is done.

The first step of the process is to grow single crystals of Cd_{1-y}Zn_yTe showing good structural quality, and an excellent planarity since this parameter is important for hybridization yield. On the lattice-matched substrates, the Cd_xHg_{1-x}Te (111) active layers are grown by Liquid Phase Epitaxy (LPE) method. Several growth parameters were explored and optimized.

The diodes processed in this study are based on a MWIR n-on-p process. Several sets of parameters were used to realize the 7.5 μ m and 5 μ m demonstrator FPAs. But we obtained more aggressive pitches, functional diodes at pitches as low as 3 μ m! One of the main challenge for small pitches ROIC design is to maintain a reasonable charge storage capacity. We succeeded with a 3Me- for the 7.5 μ m and 1Me- for the 5 μ m pitch. We also want to preserve a high signal to noise ratio (SNR), and to operate in Integrate While Read (IWR) snapshot mode with a

maximum integration time about 10ms, in order to obtain a 100Hz frame rate.

The hybridization of the ROIC to the detector die is a self-aligned flip-chip technology using Indium micro bump interconnections. This technology is well mastered and widely used down to 10 μ m pitch. We improved these processes in order to reach 7.5 μ m and 5 μ m pitches.

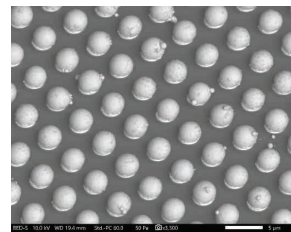


Fig. 1. Indium bumps for the 5 μ m pitch

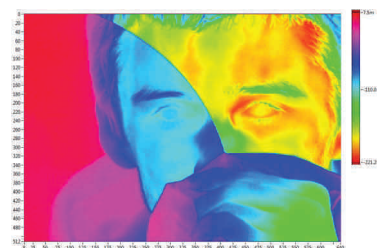


Fig. 2. Image from the 7.5 μ m demonstrator

Perspectives

The developments performed during this study have allowed an extensive understanding of the compromise between the MTF and NETD requirements to achieve small pitch FPA, and the results obtained pave the road to larger small pitches FPA at 7.5 μ m or even 5 μ m, possibly reachable in the near future.

RELATED PUBLICATIONS:

- [1] S.Bisotto, J.Abergel, B.Dupont, A.Ferron, O.Maillart, JA. Nicolas, S.Renet, F.Rochette, JL. Santailier (2019). 7.5 μ m and 5 μ m pitch IRFPA developments in MWIR at Leti CEA. SPIE Defense + Commercial Sensing Infrared Technology and Applications XLV conf 11002 11002-101
- [2] S.Bisotto, J.Abergel, B.Dupont, A.Ferron, O. Gravrand, O.Maillart, JA. Nicolas, S.Renet, F.Rochette, JL. Santailier, A.Yèche (2020). Developments towards very small pitch HgCdTe focal-plane-arrays. OPTRO 2020_00010
- [3] MAILLIART Olivier, RENET Sébastien, BERGER Frédéric, GUEUGNOT Alain, BISOTTO Sylvette, GOUT Sylvain, MATHIEU Lydie, GOIRAN Yannick, CHAIRA Tarik (2019). Assembly of very fine pitches Infrared focal plane array with indium micro balls. EMPC Pisa Italy InT-14

Assembly of very fine pitches Infrared focal plane array with indium micro balls.

RESEARCH TOPIC:

Cooled IR Imaging, Fine pitch Interconnections, Flip chip bonding, Wafer Level Packaging, hybridization

AUTHORS:

O. MAILLIART, S. RENET, F. BERGER, A. GUEUGNOT, S. BISOTTO, S. GOUT, L. MATHIEU, Y. GOIRAN and T. CHAIRA

Cooled infra-red detectors are produced using indium micro bumps interconnections at pitch as small as 10 μ m. In this study we developed new processes so as to reduce the pixel pitch to 7,5 μ m and 5 μ m. We first worked on Wafer Level Packaging processes and managed to produce Under Bump Metallization (UBM) and indium micro bumps at fine pitches. Then, these Interconnections arrays were used to develop hybridization processes on mechanical and electrical test vehicles up to a resolution of 1280 x 1024 pixels. Finally, new processes were successfully implemented to solder CMT (Cadmium Mercury Tellurium) TV range (640x512 pixels) detectors at 7,5 μ m pitch onto ROICs specially designed to fulfil the project's needs. First electro-optical characterizations revealed a connection rate higher than 99% and it has been possible to acquire IR pictures. In addition, some ageing tests have been performed on these functional detectors and an electrical (with daisy chains) 2k² demonstrator at 5 μ m pitch is to be achieved.

Context and Challenges

Flip chip is a high-density and highly reliable interconnection technology, which is mandatory for the fabrication of high end heterogeneous imaging arrays. In the field of cooled infrared detectors, indium bumps interconnections technology is well mastered and widely used down to 10 μ m pitch. Control of ultra-fine pitch (<10 μ m) flip-chip bonding technology represents a challenge on the roadmap of next generation devices. In the context of the common laboratory DEFIR with LYNRED, CEA-LETI has addressed the issue of assembling very small pitches focal-plane-arrays (FPA).

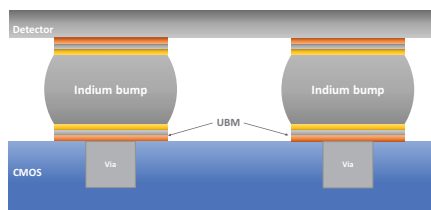


Fig. 1. Schematic representation of In bumps on UBM during hybridization

Main Results

Under Bump Metallization (UBM)

The reference process developed during the past few years leads to the creation of well-shaped and plane UBM at 15 μ m pitch (cf. figure 1-a). It consists in depositing three successive metallic layers onto the wafer and creating the UBM by ion beam etching (IBE) through a resin mask.

The reduction of the pitch from 15 μ m to 7,5 μ m and 5 μ m results in an important reduction of the UBM diameter and induce the formation of a defect during etching; a wall at the periphery of the UBM as shown in figure 1-b&c. These walls have to be removed as they will prevent the wetting of the solder on the surface of the UBM and therefore will be detrimental to the creation of a strong interconnection.

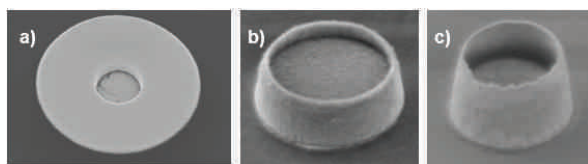


Fig. 2. UBM obtained with reference process at 15 μ m (a), 7,5 μ m (b) and 5 μ m (c) pitches

A study of the etching process (resin type and thickness, current, tension, angle) has been carried out so as to define optimized parameters for 7,5 μ m and 5 μ m pitches. Etching angle seems to be the key parameter in wall elimination; its increase is favourable to wall elimination as the beam will etch the side of the resin during the process.

The new UBM process is compatible with the production of UBM pads as fine as 1 μ m in diameter and presents the advantage of being common to 15 μ m, 10 μ m, 7,5 μ m and 5 μ m pitches.

In bumps

We used a slightly modified version of the 10 μ m pitch process for indium deposition. Indium is deposited onto a patterned resin by evaporation under vacuum in an Alliance Concept EVA 760 equipment. The Indium bumps are obtained by lifting off the resin.

Hybridization

Fine pitch joining process was developed on mechanical and functional samples to set the misalignment limit. The self-alignment assembly is achieved by a reflow of the indium μ bump interconnections on a Pick&Place SET FC300 machine with formic acid vapor. The alignment accuracy is as good as 0,5 μ m for 7,5 μ m pitch and 0,8 μ m for 5 μ m pitch. As expected SEM observations show a great proportion of intermetallic compounds inside the interconnections in comparison with bigger pitches.



Fig. 3. 7,5 μ m pitch : SEM cross section after hybridization of a 640 x 512 MCT on a ROIC

Fifteen FPA have been hybridized, characterized and tested under ageing or working conditions. Electro-optical characterizations were particularly interesting for hybridization evaluation as they allow a precise measure of the hybridization yield. The average hybridization yield measured after ageing (100 cycles between 93K and 293K, 15 minutes per cycle) is as high as 99.96% and the demonstrators fulfilled all expectations.

Perspectives

A Phd student is working on the limitation of IMC proportion in the Interconnection.

A 2k² mechanical demonstrator at 5 μ m pitch is going to be achieved in 2020.

RELATED PUBLICATIONS:

- [1] S.Bisotto, J.Abergel, B.Dupont, A.Ferron, O.Maillart, J.A. Nicolas, S.Renet, F.Rochette, J.L. Santailier; 7,5 μ m and 5 μ m pitch IRFPA developments in MWIR at CEA-Leti, Proc. SPIE. Infrared Technology and Applications, 2019
- [2] J. Abergel, F. Rochette, S. Gout, X. Baudry, C. Grangier, A. Even, J.L. Santailier, D. Giotta, R. Obrecht, T. Pellerin, L. Bonnefond, J. Rothman, S. Bisotto, Development of sub-10 μ m pitch HgCdTe infrared detectors, Proc. SPIE. Infrared Technology and Applications, 2019



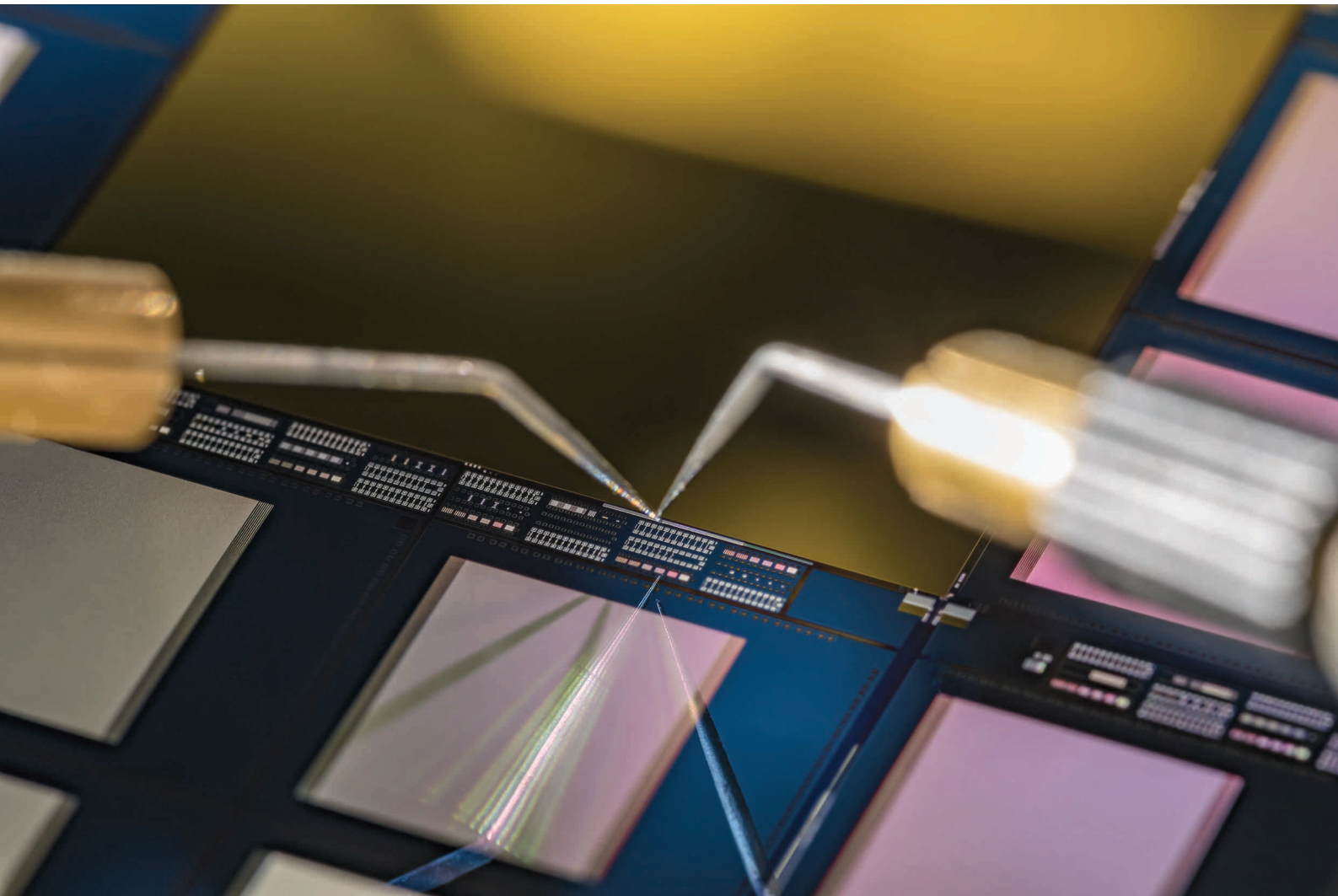


photo credit: Denis Morel

02

IR AND THZ IMAGING: **BOLOMETERS**

- **FDSOI MOSFET μ -bolometers**
- **Passive THz imaging with lateral SOI p-n junction μ -bolometers**
- **Cooled Si μ -bolometers detect polarized mm-waves**



A novel MOSFET-based uncooled sensor for disruptive IR focal plan arrays

RESEARCH TOPIC:

Microbolometers, IRFPA, FDSOI, 3D integration

AUTHORS:

A.Albouy, J.J.Yon, P.Leduc, G.Dumont, A.Aliane, F.Balestra (Univ. Grenoble Alpes, CNRS, Grenoble INP, IMEP-LAHC)

Cost reduction is one of the key issue of uncooled microbolometers. We propose a new concept of FDSOI transistor based uncooled microbolometer. In this paper, we report on a key point of the technology, namely the bonding a FDSOI transistor on a second passive silicon wafer. Low frequency noise and thermal sensitivity before and after bonding are assessed.

Context and Challenges

Thermal infrared market is constantly increasing thanks to innovations in defense and security, automotive industry and Internet Of Things (IoT). Uncooled microbolometer Focal Plane Array (FPA) is a key technology for supporting these innovations. In first insight microbolometers are composed by an absorber that heats up, a thermal transducer and a Read Out Integrated Circuit (ROIC). Thermistor materials like amorphous silicon or vanadium oxide are commonly used as thermal sensitive element. Despite tremendous progress, their fabrication requires a dedicated manufacturing line and are therefore not suited for the aim of ultimate cost reduction. One way to reduce the cost could be a bolometer integration scheme fully compatible with CMOS microelectronics processes. We propose to replace the traditional thermistor device by a Fully Depleted Silicon On Insulator (FDSOI) MOS transistor. The bolometric FPA is obtained by the bonding of the sensor wafer—comprising the absorber and the thermometer—onto the ROIC wafer thanks to hybrid molecular copper-oxide bonding. The structure is then released in vapor hydrofluoric acid (HFv) to obtain the final structure, which follows a 100% microelectronics standard process flow. In this study [1], we demonstrate a key point of the technology, namely the bonding a FDSOI transistor on a second passive silicon wafer. Thermal sensitivity and noise level are assessed before (Fig.1.A) and after bonding (Fig.1.B).

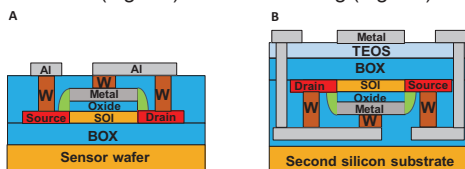


Fig. 1. Unbonded transistor (Fig 1.A) and bonded transistor (Fig 1.B)

Main Results

Fig.2.A represents the normalized noise spectral density S_{Id}/I_d^2

versus drain current I_d for unbonded and bonded transistor at $f=10\text{Hz}$. We obtained a same level of noise before and after bonding. It confirms that the operation of bonding did not degrade the interfaces of the FDSOI transistor. Unified model was applied to extract the interface trap density in the volume of the oxide N_t for both unbonded and bonded transistor. Extraction led to $N_t=1.5.10^{24}\text{m}^{-3}.\text{eV}^{-1}$. It is state of the art value for a $\text{SiO}_2/\text{HfO}_2/\text{TiN}$ gate stack. Temperature Coefficient of Current ($\text{TCC}=\frac{1}{I_d}\frac{dI_d}{dT}$) was also extracted for unbonded and bonded transistor thanks to $I_d(V_g)$ characteristics measured at 30°C and 35°C . Fig.2.B presents the TCC versus drain current for unbonded and bonded transistors. Thermal performance is the same between unbonded and bonded transistor, which denotes once again that bonding did not degrade performances of the transistor. TCC in weak inversion is besides much higher than state of the art TCR ($\text{TCR} \sim 2\%/K$) of thermistors materials.

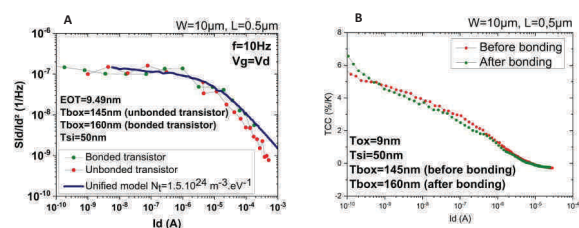


Fig. 2. Normalized noise spectral density versus drain current before and after bonding fitted with unified model (Fig 2.A). TCC versus drain current before and after bonding (Fig.2.B)

Perspectives

In this work we have assessed the feasibility of replacing thermistor materials of uncooled microbolometer by FDSOI transistor: Thermal performance and noise level are the same after the bonding of the transistor on a second silicon wafer. These results open the path to low cost standard CMOS integration scheme for microbolometers.

RELATED PUBLICATIONS:

[1] A.Albouy, J.-J.Yon, P.Leduc, G.Dumont, A.Aliane, F.Balestra. A novel MOSFET-based uncooled sensor for disruptive IRFPA. Proceedings of Optro2020, 2020.

High performance SOI lateral p-n junction bolometric detector for passive THz imaging

RESEARCH TOPIC:

THz detectors

AUTHORS:

J. Blond, A. Aliane, J. Meilhan, L. Dussopt

THz imaging enables the detection of objects through Degraded Visual Environments, such as brownout clouds. Such application is very challenging and still lacks high sensitivity large-size detector arrays. The development of a silicon-based THz bolometric pixel enabling passive imaging would be a considerable progress over the current state of the art in THz imaging. Lateral SOI p-n junction thermometers, cooled at liquid-N₂ temperature, could represent a relevant solution for such high-sensitivity bolometer detector. In this project, thermometer prototypes have been developed and characterized in thermal sensitivity and noise with promising performances.

SCIENTIFIC COLLABORATIONS: This work is partially supported by the Defense Innovation Lab from the French Ministry of Defense.

Context and Challenges

THz imaging triggers interests in many applications: security, surveillance, non-destructive testing, biomedicine, etc. Among them, the detection of hidden objects or imaging in Degraded Visual Environments, e.g. through dust or sand clouds, are very challenging in terms of sensitivity. In such applications, passive imaging may be the preferred solution to mitigate the lack of high power sources and retro-diffusion effects. However, state-of-the-art THz detector arrays enabling passive imaging require a cryogenic cooling below 10 K incompatible with outdoor and transportable systems. This project aims at developing a high sensitivity silicon-based THz bolometer pixel, operating under moderate cryogenic cooling (80 K N₂ cooling) and based on lateral p-n junction thermometers.

Main Results

Lateral p⁺-n-n⁺ SOI diodes have been fabricated on 4 inches SOI wafers at the UpStream Technological Platform of Renatech in Grenoble (renatech.org). A thin SOI layer of 50 nm was chosen to minimize the heat capacity of the future bolometer in the perspective of real-time imaging. SEM image of a test device and a schematic cross section are presented in Fig. 1.

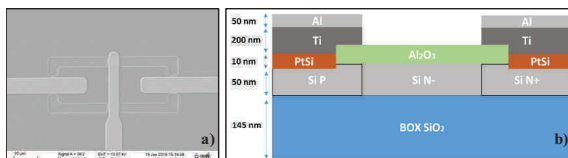


Fig. 1. (a) SEM top view of the fabricated diode with etched mesa configuration. (b) Schematic cross-section of device.

SILVACO® TCAD has been used to set up the doping process parameters and perform the device simulations. The maximum Temperature Coefficient of Current (TCC) is obtained in the diffusion regime of the diode, due to the built-in potential increase when lowering the temperature. A TCC up to 22%/K

is found in simulation for a lateral diode with a n⁻ region length $L = 20 \mu\text{m}$ at 80 K and a normalized bias current of $1 \text{ pA}/\mu\text{m}$.

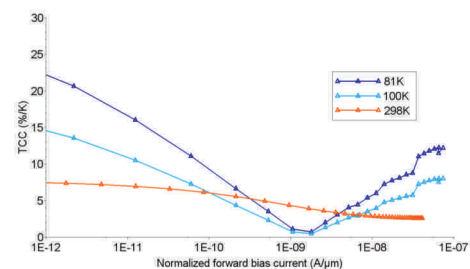


Fig. 2. Absolute value of the TCC at several temperatures for an annealed mesa diode.

Fig. 2 presents the experimental TCC of a diode in mesa configuration after a post-process N₂H₂ annealing. The thermal responses are in good agreement with the simulations at low forward bias currents while a significant discrepancy is observed in high injection regime and low temperature due to excessive specific contact resistances. Nevertheless, a TCC up to 22%/K (81 K, $1 \text{ pA}/\mu\text{m}$ bias) is obtained as predicted by the simulation. Noise measurements showed a $1/f$ noise response in the range of $10 \text{ fA}/\text{Hz}^{1/2}$ at 1 Hz for low-level injection. TCC and noise performances enable a coarse estimation of the intrinsic MDP lower than 10 pW for these thermometer prototypes.

Perspectives

These first results validate the behavior and modeling of thin SOI lateral p-n junctions operating at 80 K and low injection regime in terms of thermal response and noise. The fabrication of optimized samples is in progress with an expected gain of at least one order of magnitude in sensitivity.

RELATED PUBLICATIONS:

[1] J. Blond, J. Meilhan, A. Aliane and L. Dussopt, "Cooled Silicon-On-Insulator Diode Thermometer: Toward THz Passive Imaging," 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Paris, France, 2019, pp. 1-2, doi: 10.1109/IRMMW-THz.2019.8874022.

Mechanical modeling and characterization of suspended cooled silicon bolometers for sub-millimeter and millimeter waves polarization detection

RESEARCH TOPIC:

Mm-wave and THz detectors

AUTHORS:

A. Aliane, J.-L. Ouvrier-Buffet, L. Dussopt, V. Goudon, W. Rabaud, H. Kaya, R. Torrecillas, P. Agnès, O. Adami (IRFU), L. Rodriguez (IRFU), V. Réveret (IRFU), A. Poglitsch (Max Planck Inst.)

Silicon bolometers, cooled at sub-kelvin temperatures, have been used successfully for many years as sub-millimeter wave detectors in ground and space-based telescopes for astrophysics applications. Addressing millimeter-wave bands with this technology involves several technological challenges, in particular regarding their large suspended structures that are prone to mechanical deformations due to internal stress and thermal expansion coefficient differences among materials. In this work, we investigated the mechanical behavior of silicon bolometers with a pixel pitch of 500 and 1200 μm , and we demonstrated, both theoretically and experimentally, very promising results in terms of limited and controlled deformations.

SCIENTIFIC COLLABORATIONS: CEA-IRFU, LABEX FOCUS (ANR-11-LABX-0013)

Context and Challenges

Silicon bolometers consist of absorbers and thermometers that are thermally insulated and suspended about 2.5 μm only above an optical cavity and a read-out circuit. The thermometer is critical in the electrical and optical performances. It requires a high sensitivity, a low thermal conductivity and capacity, and a very good mechanical stability once suspended. Its mechanical deformations after release are due to residual stresses coming essentially from the fabrication process. In the case of large-size detectors, the mechanical stability is particularly challenging to prevent any contact to the substrate (thermal shorting) and to support the radiation absorbers in optimal (flat) position.

Main Results

Two different pixels, with a size of 500 and 1200 μm , were designed and fabricated for the 600 and 1500 μm wavelengths, respectively. Each pixel combines four active bolometers, detecting either the vertical or horizontal polarization component, and four reference bolometers (Fig. 1). The suspended structure of the active bolometers is a multi-layer stack composed of doped crystalline silicon (thermometer), an amorphous silicon (a-Si) layer for electrical isolation, a metal absorber (Ti/TiN) and another a-Si layer for passivation.

We investigated the mechanical behavior of the suspended structure through theoretical modeling, finite element method (FEM) simulation and experimental measurements [1]. The multiple layers of this structure are modeled as an equivalent layer with effective Young's modulus, thickness and residual stresses. Residual stresses mainly consist of a constant average component, which results from the coefficient of thermal expansion (CTE) mismatch between layers, and a gradient component, which is due to localized effects.

From cantilever test structures, which were modeled and fabricated, these effective parameters could be extracted and used in the FEM simulation model of the pixels. These simulation results showed a good agreement with experimental measurements performed at room temperature on actual pixels (Fig. 2). Finally, the deformations were simulated at low

temperature, down to the operating temperature of the detectors (0.1 K), by taking into account the CTE mismatch effects between deposited materials. The very limited displacements, between -0.05 and +2.5 μm , obtained in these simulations meet the requirements for optimal performance of the detectors.

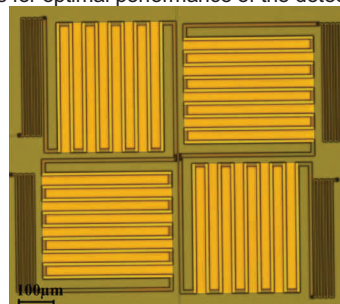


Fig. 1. Photograph of a fabricated pixel with a pitch of 1200 μm before releasing.

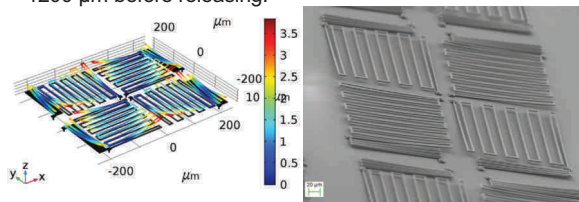


Fig. 2. FEM mechanical simulation and scanning electron microscope image of a 500- μm released pixel.

Perspectives

The silicon bolometer detectors presented in this work achieve state-of-the-art performances with a Noise Equivalent Power (NEP) in the range of 2–10 $\text{aW}/\text{Hz}^{0.5}$ for an optical load of 6 fW at 0.1 K. The modeling methodology and technology know-how demonstrated in this work are used in our current development of detector arrays for the B-BOP instrument of the SPICA telescope [2].

RELATED PUBLICATIONS:

- [1] A. Aliane et al., "Mechanical modeling and characterization of suspended cooled silicon bolometers for sub-millimeter and millimeter waves polarization detection", *Sensors and Actuators A* 296 (2019) 254-264.
- [2] O. Adami et al., "Highly sensitive polarimetric camera (B-BOP) for the SPICA mission", *Applied Optics*, vol. 58, no. 2, pp. 398-403 (2019).



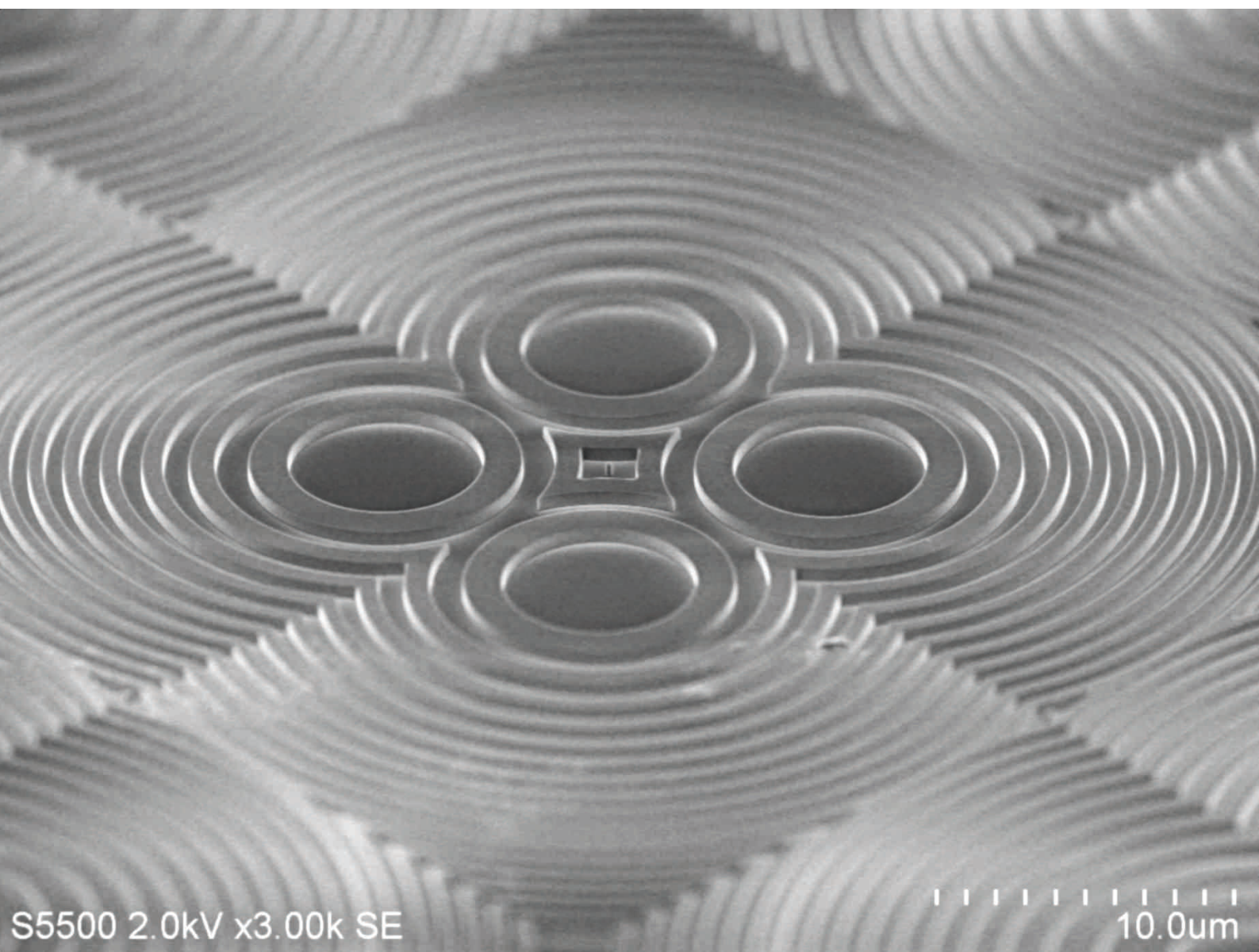


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O3

CMOS IMAGING

- **SWIR vertical p-i-n Ge photodiodes**
- **Diffraction micro lenses improve sensitivity of SPAD arrays**
- **Collective process to curve CMOS sensors**
- **Mixing wave optics simulations with ray tracing simulations for computational imaging**
- **1/f noise in imaging pixels**
- **Noise and electromagnetic coupling in sequential 3D technologies**
- **Noise influences color rendering: a geometrical interpretation**
- **Parallel acquisition-processing in 3D stacked vision chips**
- **Compressive sensing in image sensors**
- **An imager associated with AI: a simulation framework**
- **Near-sensor decision making for AI**

Fabrication and characterization of vertical P-i-N Germanium Photodiodes

RESEARCH TOPIC:

Infrared detectors, Germanium photodiode, SWIR

AUTHORS:

A. Aliane, J.-L. Ouvrier-Buffet, W. Ludurczak, L. André, H. Kaya, C. Vialle, M. Benwadih (LITEN/DTNM), V. Goudon, S. Becker and J.-M. Hartmann (LETI/DPFT)

Detection in SWIR band is very attracting for various applications such as military, security and in commercial products such as in telecommunication applications and medical diagnostics. The SWIR light presents many advantages compared to the visible light; it is invisible to the human eye and is less sensitive to extreme weather conditions such as fog and dust. Detection in the SWIR band is based on quantum detectors, which convert photons directly into charge carriers without any intermediate process involving. The use of the Germanium as an active layer in the PiN photodiodes presents many advantages such as its good absorption and its compatibility with the mass-production processes used in the silicon microelectronics industry. In this work, Ge/Si vertical PiN devices were developed, fabricated and characterized at room temperature with promising performances such as a low dark current density and good external responsivities.

SCIENTIFIC COLLABORATIONS: mentionner les noms d'entités autres que Leti

Context and Challenges

Germanium on silicon P-i-N photodiodes for NIR and SWIR bands have been studied and fabricated using standard CMOS technologies. The main goal of the project is to achieve a very low dark current density and a high responsivity with a smaller pitch. The strain engineering in the Ge photodiode is an another challenging topic in order to absorb beyond 1550 nm which is the cut-off wavelength of an unstrained Germanium layer.

Main Results

Different designs of vertical Ge/Si PiN photodiodes were fabricated and characterized. The active part of the PiN is an intrinsic Germanium epilayer with a 1.5 μm thick, grown at 750°C, 20 Torr by RPCVD. This Ge epilayer presents a threading dislocations density (TDD) of 10^7cm^{-2} . Figure 1 depicts SEM images of fabricated devices with a pitch of 10 μm .

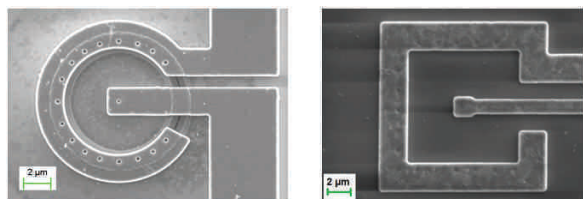


Fig. 1: SEM image of a circular (left) and a square (right) shape of a Ge photodiode

I-V measurements at room temperature were performed on fabricated devices showing a good diode behavior notably, a ratio I_f/I_d of 1.8×10^5 at +1V/-1V and a dark current density of 573 $\mu\text{A}/\text{cm}^2$ at -1V (Fig.2a).

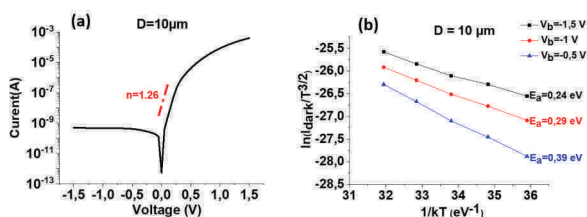


Fig. 2: Electrical characterizations of a Ge photodiode with $D=10\mu\text{m}$, (a): Dark current $I(V)$ measurements and (b) Extraction of the dark current activation energy.

An activation energy (E_a) of 0.29 eV is extracted at -1 V corresponding to half the Ge indirect band gap, indicating an SRH process via deep levels in the forbidden gap (Fig.2b).

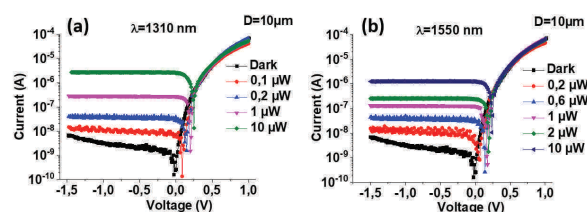


Fig. 3: Photocurrent characteristics at different powers for a photodiode with $D=10\mu\text{m}$ at: (a) $\lambda=1310\text{nm}$ and (b) $\lambda=1550\text{nm}$

External responsivities of 0.275 and 0.133 A/W at $\lambda=1310\text{ nm}$ and $\lambda=1550\text{ nm}$, respectively was measured without any antireflective coating (ARC) layer for a 10 μm pitch (fig.3)

Perspectives

First results on Germanium photodiodes are very promising. A reduced TDD of 10^7cm^{-2} and a dark current density of 573 $\mu\text{A}/\text{cm}^2$ at -1V were obtained respectively for the Ge epilayer and for the fabricated PiN device. Future optimizations of the design and of the technological process is in progress to achieve lower dark current densities and higher responsivities.

RELATED PUBLICATIONS:

[1] A. Aliane, J.-L. Ouvrier-Buffet, W. Ludurczak, L. André, H. Kaya, C. Vialle, M. Benwadih, V. Goudon, S. Becker, J.-M. Hartmann, "Fabrication and characterization of sensitive vertical P-I-N germanium photodiodes as infrared detectors", Semiconductor Science and Technology, 35, 035013, (2020).

SPAD array sensitivity improvement by diffractive microlens

RESEARCH TOPIC:

Image sensors

AUTHORS:

J. Vaillant, L. Masarotto, R. Paquet, V. Lecoutre, C. Pellé, N. Moussy, S. Jouan (STMicroelectronics)

We improve the sensitivity of SPAD pixel with planar diffractive lens. We firstly designed microlens structures based on rigorous optical simulations, then we developed the process for thick optical spacer and thin amorphous silicon deposition, on which diffractive structures were defined by lithography and etching. These microlenses were implemented on two SPAD designs available on STMicroelectronics 40nm CMOS testchips (32x32 SPAD array). Circuits were characterized and we demonstrated, depending on SPAD design, high optical gain at 850nm (x2.7 to x5.3) and significant gain at 940nm (x1.6 to x2.4).

SCIENTIFIC COLLABORATIONS: STMicroelectronics TR&D, 850 rue Jean Monnet, F-38920 Crolles

Context and Challenges

Single Photon Avalanche Diode (SPAD) arrays are promising image sensors for applications requiring photon arrival timestamp with accuracy around hundreds of picoseconds or even less. From an optical point of view, the main limitation of SPAD pixels is their low optical fill-factor, about 10% or below. This can be partially overcome by placing light concentrator in front of each pixel. In this work, we present the development of wafer level diffractive microlens on top of SPAD for applications in near-infrared (between 850nm and 950nm).

Main Results

To concentrate light onto SPAD photodiode, we considered Fresnel Zone Plate structures (FZP). It consists of rings diffracting the light to produce constructive interferences at the focal point and size of rings are calculated using Fresnel zone. In order to take profit of all incident light, a phase shift is introduced by the material of the rings, so light diffracted in-between rings and by rings add constructively at the lens focus. We chose amorphous silicon (a:Si) as it presents advantageous properties: it is compatible with CMOS process, has very low absorption in the spectrum of interest and thanks to its high refractive index, the phase shift can be introduced while keeping the layer thickness low, further reducing the absorption and making the patterning easier. FZP structures were simulated by rigorous electromagnetic simulation (FDTD) and their optimization done with Surrogate Based Design Optimization (SBDO) toolbox developed at CEA-LETI (<https://github.com/freeSBDO/SBDOT>).



Fig. 1. Vertical cross-section of optical spacer and a:Si microlens processed on CMOS wafer

We developed wafer level process for both optical spacer and FZP structure. Thick oxide low temperature deposition (350°C PECVD) forms a 10μm pedestal before a:Si deposition (low power PECVD), see Fig 1. Fresnel Zone Plate structures are formed on a:Si layer by deep-UV, see Fig 2.

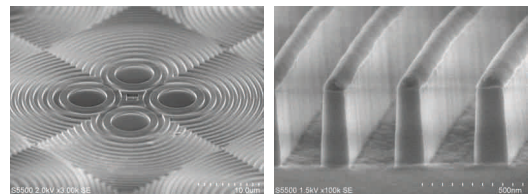


Fig. 2. Tilted SEM view of FZP structures implemented on 2x2 SPAD (left), SEM view of pattern with CD = 100nm after etching (right).

In order to implement few design variants of FZP on the 32x32 SPAD arrays while ensuring statistically representative sampling, we split the image into 8 areas of 8x16 SPADs. One of them was kept free from microlens and serves as reference for measurement. Devices were characterized using in-house characterization capabilities. We achieved an optical gain of x5.3 at 850nm for centered SPAD design, and x3.3 at 850nm for offcentered SPAD design. This latter lower gain is mainly due to the 2:4x higher optical fill factor (12% versus 5%) and the strong off-axis leading to more interaction between light and the metallic interconnections, thus reducing the light concentration capability of the lens.

Perspectives

Results on this first implementation of FZP microlenses on SPAD are very encouraging and to the best of our knowledge this is the highest optical gain demonstrated with diffractive microlens on SPAD, comparable or exceeding results obtain with refractive microlens. In addition, this technology offers several advantages like planar and inorganic microlens or the capability to design off-axis microlens.

RELATED PUBLICATIONS:

[1] J. Vaillant et al., « SPAD array sensitivity improvement by diffractive microlens », in Proc. Int. Image Sens. Workshop, 2019, p. 4

Collective curved CMOS sensors process: application for high-resolution optical design and assembly challenges

RESEARCH TOPIC:

Curved CMOS sensors, Collective process, Imaging systems, Optical design, Optical aberrations, Petzval field curvature, Photography, Mechanical limits, Electro-optical characterization.

AUTHORS:

B.Chambion, C.Gaschet, M. Lombard, M. Fernandez, P. Joly, S.Caplet, F.Zuber, A.Vandeneynde, P.Peray, G.Lasfargues, M. Zussy, J. Deschamps, A. Bedoin, D.Henry.

Curved sensors is a well-adapted technology solution to enhance a vast majority of optical systems. It helps to remove lenses and simplify optical architectures. We first introduce benefits of curved sensors applied on a compact high-resolution camera to define the sensor shape specifications and to reach high performances and compactness (-60% compared to a benchmark system). Mechanical limits and optical modeling are used. Then, a collective curving process is developed on 1/1.8" format CMOS image sensors with a radius or curvature target $R=55\text{ mm}$ and $R=60\text{ mm}$. This work includes packaging and assembly steps, optimizations, and morphological characterizations in accordance to optical design requirements. A dedicated optical test bench is used for Modulation Transfer Function (MTF) characterization of the final camera prototype. All these experiments and optic results introduce new opto-mechanical requirements and demonstrate the feasibility and high performances of systems with curved sensors [1].

Context and Challenges

The need for curved focal planes in optical designs has been known by opticians since Joseph Petzval 180 years ago and proved in further researches. To apply this concept to CMOS image sensors, the technical challenges are to curve a monolithic CMOS component without causing mechanical and electro-optical failures. In [2-3], our previous developments on the curvature of monolithic sensors show the feasibility to curve CMOS sensors without electro-optical performance loss.

Main Results

In this work, we introduce a collective curved CMOS process applied to a standard 1/1.8" format image sensor. First, mechanical considerations have to be taken into account to define the boundaries of the reachable curvatures (Fig. 1). These inputs are integrated into the optical design step so that we are able to specify the sensor surface shape to fabricate.

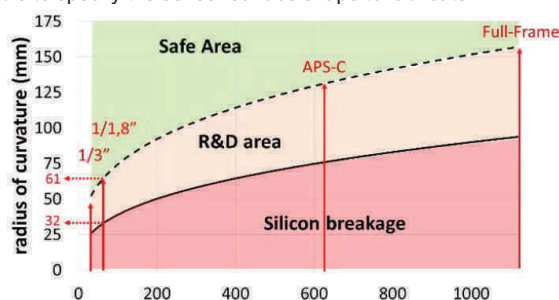


Fig. 1. Results of breakage limits considering two failure criteria. $\sigma_{1\max1} = 200\text{MPa}$ (dash line) and $\sigma_{1\max2} = 500\text{MPa}$ (solid line), for different formats (thickness: $100\text{ }\mu\text{m}$).

As this work is built on a 1/8" sensor format, the minimum allowable radius of curvature is $R=32\text{ mm}$ for $\sigma_{1\max2} = 500\text{MPa}$ and $R=61\text{ mm}$ for $\sigma_{1\max1} = 200\text{MPa}$.

Then, our collective curving process is applied to finally obtain a curved sensor in its ceramic package. Main steps are chip thinning, curved holder fabrication, curving process (Fig. 2) and packaging integration (die attach and wirebonding).

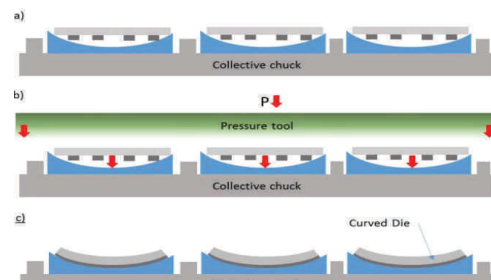


Fig. 2. Collective curving process step details. a) Flipped chip on curved holder. b) Die shaping and die attach curing. c) Pressure tool release.

Then, packaged curved sensors are mounted onto a PCB and integrated within a camera module with optimized optics. MTF has been measured and compared with a flat image sensor integrated within a commercial optics system (Fig. 3).

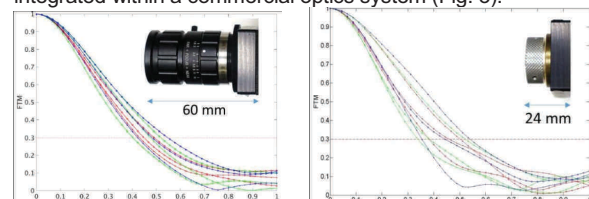


Fig. 3. MTF measurement of a commercial (left) compact design Techspec® with flat CMOS sensor and (right) a compact camera prototype equipped with curved CMOS sensor ($R=55\text{mm}$).

We demonstrated that, thanks to curved sensors, we can obtain the same optical performances as for a flat one but with a dramatically more compact system (60% less length in our case).

Perspective

Future work and perspectives include the development of collective fabrication process for the curved holder and more compact packaging solution for curved sensor (ex: chip size package / CSP).

RELATED PUBLICATIONS:

- [1] B. Chambion et al., "Collective Curved CMOS Sensor Process: Application for High-Resolution Optical Design and Assembly Challenges," 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2019, pp. 535-542.
- [2] B. Chambion, C. Gaschet, T. Behaghel, A. Vandeneynde, S. Caplet, S. G  tin, D. Henry, E. Hugot, W. Jahn, S. Lombardo, M. Ferrari, "Curved sensors for compact high-resolution wide-field designs: prototype demonstration and optical characterization", Proc. SPIE 10539, 1053913 (2018).
- [3] B. Chambion, L. Nikitushkina, Y. Gaeremynck and W. Jahn, "Tunable curvature of large visible CMOS image sensors: Towards new optical functions and system miniaturization," 2016 IEEE 66th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, 2016, pp. 178-187

Joint electromagnetic and ray-tracing simulations for quad-pixel sensor and computational imaging

RESEARCH TOPIC:

Image sensors

AUTHORS:

G. Chataignier (InterDigital), B. Vandame (InterDigital), J. Vaillant

Since Canon released the first dual-pixel autofocus in 2013, this technique has been used in many cameras and smartphones. Quad-pixel sensors, where a microlens covers 2x2 sub-pixels, will be the next development. In this paper we describe the design for such sensors; related wave optics simulations; and results, especially in terms of angular response. Then we propose a new method for mixing wave optics simulations with ray tracing simulations in order to generate physically accurate synthetic images. Those images are useful in a co-design approach by linking the pixel architecture, the main lens design and the computer vision algorithms.

SCIENTIFIC COLLABORATIONS: InterDigital, 975 Avenue des Champs Blancs, Cesson-Sévigné, 35576, France

Context and Challenges

Development of sub-micron pixels offers new opportunity for non-conventional imaging (*R. Ng et al., Light field photography with a hand held plenoptic camera, Tech. rep., Stanford Univ. (2005)*). In this study we investigate the quad-pixel structure using 2x2 photodiodes for one microlens. This is an extension of currently available Phase-Difference Detection Auto-Focus (PDAF (*M. Kobayashi et al., Jpn. J. Appl. Phys. 57, 1002B5 (2018)*)) which uses 2 photodiodes for one microlens to generate disparity signal for auto-focus driver. Quad-pixel extends the capabilities to bokeh improvement or depth extraction. Nevertheless, algorithms still need to be developed and require input images. As no sensor is currently available, we developed a new simulation framework that combine electromagnetic simulation at pixel level and realistic ray-tracing simulations for scene rendering.

Main Results

We simulated quad pixels of $1.75 \mu\text{m}$, using Finite Difference Time Domane (FDTD) software, for multiple angle of incidence and different Chief Ray Angle Correction (translation of the microlens with respect to the center of the quad pixel). We obtained a 4 dimensions angular response which characterize the diffraction and the cross talk between the 4 sub-photodiodes. This angular response has been used to render the effects of diffraction at pixel level in a ray tracing software. The method consists in weighting each ray by a factor given by the angular response. Then the ray is added to the neighboring photodiodes hence simulating the cross talk [Fig.1].

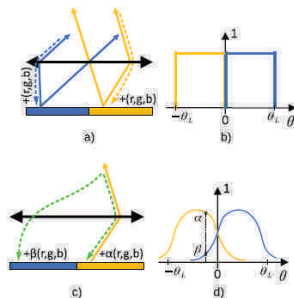


Fig. 1. (a) and (b) show the classic ray tracing procedure and its ideal angular response. (c) and (d) show our modified ray tracing procedure and its angular response. We were able to render synthetic images [Fig.2] as realistic as possible: scene, illumination, main lens and pixel diffraction.

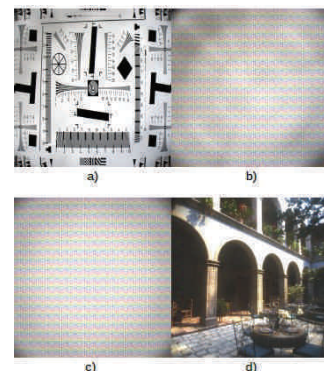


Fig. 2. Examples of synthetic images using a quad-pixel sensor made of $1.75 \mu\text{m}$ sub-pixels and ML-1 as main-lens. (a) and (b) are the SAI-A of the ISO-12233 and "abcd" test chart. (c) and (d) are the sum of the 4 SAIs of the abcd test chart and San-Miguel scene respectively.

Those images were used to demonstrate that disparity-based algorithms are less efficient when quad pixels become small, because the diffraction by the microlens causes too much sub-photodiode cross talk. We took an aberrations correction algorithm as an exemple at the end of the paper.

Perspectives

A quad-pixel sensor offers new possibilities in terms of computational imaging, but it is really important to get the best imaging pipeline, especially with small sub-pixels. We will use this tool to generate image database that will be our ground truth in terms of depth map and demosaicing. Then we will be able to train machine/deep learning networks and eventually get even better results than traditional algorithms.

RELATED PUBLICATIONS:

[1] G. Chataignier, G. Chataignier, B. Vandame, et J. Vaillant, « Joint electromagnetic and ray-tracing simulations for quad-pixel sensor and computational imaging », *Opt. Express*, OE, vol. 27, n° 21, p. 30486-30501, oct. 2019, doi: 10.1364/OE.27.030486

Correlated Multiple Sampling impact analysis on $1/f^E$ noise for image sensors

RESEARCH TOPIC:

Image sensor, $1/f$ noise, Correlated Double Sampling, Correlated Multiple Sampling, pixel

AUTHORS:

A. Peizerat, G. Renaud

Correlated Multiple Sampling (CMS), which is an extension of Correlated Double Sampling (CDS), is a very popular noise reduction technique used in the readout chain of image sensors. It has been analyzed in the literature, showing that, with an increasing number M of samples, the total noise tends to a limit value dominated by the pixel $1/f$ noise. Nevertheless, this approach fails to explain why, in some cases, the total noise measurement may reach a minimum before, against all odds, finally growing with M . This paper shows that an explanation can be found if the pixel noise Power Spectral Density (PSD) varies in $1/f^E$ with a frequency exponent $E > 1$ instead of $E=1$.

SCIENTIFIC COLLABORATIONS: Pyxalis

Context and Challenges

The low noise feature is a growing need for an image sensor as it determines its low light performance, which is of critical interest in applications like automotive, surveillance, scientific imaging or space. Several papers report an Input Referred Temporal Noise (IRTN) below the electron value where process and design are optimized. Among the noise reduction techniques that have been studied, a particular one, the Correlated Multiple Sampling (CMS), raised large interest from the imaging community. Its impact on the noise is well documented, showing that, except for high speed imagers, the remaining noise is the $1/f$ noise. The behavior of this remaining noise is predicted by an analysis based on an ideal pixel Power Spectral Density (PSD) following a $1/f^E$ curve with a frequency exponent E strictly equal to 1. Previously published works showed that E can be measured somewhere in between 0.7 and 1.3, those variations being mainly due to the oxide nature and its spatial distribution of traps. The present paper gives an insight of the CMS impact for a pixel exhibiting a $1/f^E$ noise with $E \neq 1$.

Main Results

A test-chip has been fabricated in a 90nm CIS CMOS process. Different pixels have been implemented in the matrix of a generic frame called "Creapix" developed by the company Pyxalis. Among six different 4T pixel versions, two are of interest for the purpose of this paper, each pixel version implemented in a 40x400 pixel array with the readout chain given in Fig. 1.

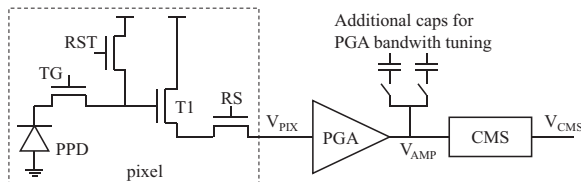


Fig. 1 Analog readout chain diagram for our test-chip

Pixel version	CG	T_{CMS}	f_c	Measured IRTN
Pixel 1	195 μ V/e-	5 μ s	450kHz	0.55e-
		15 μ s	150kHz	0.64e-
		45 μ s	50kHz	0.69e-
Pixel 2	140 μ V/e-	5 μ s	450kHz	0.56e-
		15 μ s	150kHz	0.63e-
		45 μ s	50kHz	0.68e-

Table 1: Measured IRTN

Noise results are shown in Table 1 for the order $M=1$ (i.e. a simple CDS), with $2\pi f_c T_{CMS} = \text{constant}$ and for 3 different values for f_c , f_c is the PGA bandwidth. Despite the fact that pixel versions have a significant different CG, the measured Input Referred Temporal Noise (IRTN) show the same behavior. The classic noise formula (with $E=1$) predicts a smaller contribution of the thermal noise (as f_c decreases) and a constant contribution of the $1/f$ noise. So it fails to explain the increasing measured noise when f_c decreases. On the contrary, the new equation below with $M=1$ and $E>1$ can explain such a behavior:

$$IRTN = \sqrt{\frac{f_c}{f_0} \cdot N_{TH,0}^2 + \left(\frac{f_0}{f_c}\right)^{E-1} \cdot N_{1/F,0}^2} \quad (1)$$

With $f_0=450\text{kHz}$, $N_{TH,0}=0.21$ and $N_{1/F,0}=0.52$, a value of 1.3 for the exponent E seems as a good candidate to explain why measured IRTN increases when f_c decreases, as shown in Table 2.

E	$N_{TH,0}$	$N_{1/F,0}$	f_0/f_c	Predicted IRTN
1.3	0.21e-	0.52e-	1	0.56e-
			3	0.63e-
			6	0.69e-

Table 2: Predicted IRTN according to equation (1)

Perspectives

The noise optimization will result from a trade-off between the CMS order M and the bandwidth value f_c .

RELATED PUBLICATIONS:

[1] "Correlated Multiple Sampling impact analysis on $1/f^E$ noise for image sensors", A. Peizerat, G. Renaud, Electronic Imaging 2019

Impact of noise and electromagnetic coupling in sequential 3D technologies

RESEARCH TOPIC:

SOI, CMOS, Fully Depleted, Monolithic 3D, 3D Sequential Integration, stacked, coupling

AUTHORS:

Petros Sideris (IMEP-LAHC / CEA), Christoforos Theodorou (IMEP-LAHC), Perrine Batude, Gilles Sicard

3D sequential integration, also named 3D monolithic integration or 3D VLSI, refers to a 3D integration scheme where CMOS devices are fabricated sequentially in tiers stacked above each other. Thanks to the high precision alignment of lithography steppers, this process leads to an outstanding high-density-contacts between tiers (up to 108 3D via/mm²) compared to traditional packaging integration schemes (TSV, Copper to Copper bonding etc.). The scope of this PhD work is to identify the origin of the inter-tier electromagnetic coupling in 3D sequential integration and conclude in decoupling solutions through a qualitative examination of several integration scenarios for the sequential tiers.

SCIENTIFIC COLLABORATIONS: IMEP-LAHC Laboratory (Grenoble, Fr.), MINOS LabEx - ANR-10-LABX-55-01

Context and Challenges

For 3D sequential integration utilizing SOI transistors with no Ground Plane (GP), the ultra-thin Inter-Layer Dielectric (ILD) separating the sequential tiers can act as a Back Gate (BG) oxide for the top transistors, becoming a pathway of electrical interference between stacked devices (Fig.1-Left). Consequently, the top device is an asymmetrical SOI MOSFET sensitive to the bottom device electrode voltage variations or iBEOL metal biasing.

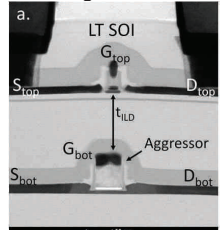
The opposite electrostatic coupling effect from the top to the bottom can only occur when the gate of the bottom device is not biased, i.e. floating, otherwise its gate metal layer is shielding the bottom channel from any electric field penetration from the top transistor gate bias. There are several circuit designs with such a configuration, e.g. ring oscillator, however they have been not studied extensively yet. Through experimental and simulation results, we managed to identify the main causes of the static and the dynamic capacitive between the sequential tiers, focusing on the top tier devices.

Main Results

First, a study of coupling-induced effects in the static and noise behavior of 3D sequential top tier transistors has been made. Through both measurements and simulations, it was shown that the coupling-induced ΔV_t , ΔI_{off} and ΔI_{on} have high values considering analog applications, however they are within the local variability limits of 28nm FDSOI technology for digital circuits, where sub- μm devices are used. In addition, it was demonstrated that the coupling effect can be limited either by increasing the ILD thickness or through a top/bottom transistor misalignment. Finally, no coupling-induced impact was observed for the low frequency noise performance of the top tier transistor [1].

Next, we have shown that, for purely digital 3D sequential circuits there is no major coupling between top and bottom tiers, therefore inter-tier GP integration is not needed. However, when it comes to mixed signal and RF applications, a polysilicon GP layer provides the necessary immunity to inter-

tier coupling effects like crosstalk (Fig.1-right). We have also demonstrated a novel integration scheme of inter-tier isolation with a polysilicon GP, highlighting its SOI compatibility and the advantages over metallic solutions [2].



	TOP TIER	Digital ($V_{DD}=1V$)	Mixed signal/RF
BOTTOM TIER	Digital ($V_{DD}=1V$)	No GP needed, $t_{ILD}=130nm$ (Verified with SRAM cell)	GP needed depending on frequency and layout of the application
	RF	For typical digital logic level noise margins, GP may not be needed	
	Analog ($V_{DD}=2.5V$)	$t_{ILD}=350nm$ or GP insertion (Due to $V_{th, top}$ shift)	GP needed (Verified with RO case)

Fig. 1. Left: TEM cross-section of two stacked transistors fabricated in 3D sequential. Right: conclusion on including or not a decoupling layer between the sequential tiers depending on each application.

Perspectives

This study is going to be completed with the mathematical modeling of the inter-tier coupling effects. The model is intended to cover all the electro-static/dynamic and noise related effects for the top-tier devices where the planar PEX tools are not valid yet. A wide range of geometries for thin film transistors with or without iBEOL as well as several geometric configurations for the bottom-tier devices are going to be modeled accurately. Obtained results yet will be utilized for the specific case of a CMOS imager made in 3D sequential integration. It is considered as an ideal case study because it is very sensitive to noise and electromagnetic coupling effects. In particular, the stacking of heterogeneous blocks, the minimization of all kinds of coupling between tiers, the boost of the image sensor performance metrics and the increment of the overall pixel fill factor, are challenges, which should be accomplished in 3D sequential integration. Over and above, that subject is considerably relevant at an industrial level and can demonstrate to a great extent the benefits and possibilities of 3D sequential integration.

RELATED PUBLICATIONS:

- [1] P.Sideris et al., "Impact Of Inter-Tier Coupling On Static And Noise Performance in 3D Sequential Integration Technology", Joint International EUROSOL Workshop and International Conference on Ultimate Integration on Silicon (EUROSOL-ULIS), Grenoble, France, April 1-3, 2019
- [2] P.Sideris et al., "Inter-tier Dynamic Coupling and RF Crosstalk in 3D Sequential Integration", IEEE International Electron Devices Meeting (IEDM), San Francisco, USA, December 7-11, 2019

Physical noise propagation in color image construction: a geometrical interpretation

RESEARCH TOPIC:

Colorimetry, image rendering, signal to noise ratio

AUTHORS:

Axel Clouet, Jérôme Vaillant, David Alleysson (LPNC Univ. Grenoble Alpes)

In order to study the noise propagation from raw acquisition to displayable image and the impact of color correction, we developed a geometrical framework. The acquisition is the projection of physical spectra onto a sensor space, these raw data are then projected on a display space. Thus, the color correction is related to the metric of this space and non-orthogonality of sensor basis affects the noise propagation. Comparative simulations between classical color sensor and low light imager show that despite higher raw SNR in the latter case, noise in color image is more visible. Geometrical characteristics of sensor space cause this degradation: higher correlation between spectral channels and near infrared part of the signal in the raw data, which is not intrinsically useful for color.

SCIENTIFIC COLLABORATIONS: Laboratoire de Psychologie et NeuroCognition, CNRS UMR 5105, Univ. Grenoble Alpes

Context and Challenges

Conventional color image sensors includes red, green and blue color filters (RGB) and infrared cutoff filter to limit the sensitivity of silicon to the human visible domain. This ensures accurate color rendering but reduces the amount of light that silicon is able to detect. In order to increase the raw signal in low light conditions, one may use RGBW sensors without infrared cutoff filter. The additional white pixel (W) ensures color accuracy and exhibits the highest raw signal to noise ratio. Nevertheless, the final color images are more noisy than the one capture with equivalent RGB sensor with infrared cutoff filter. In our study we investigate the origin of this behavior based on an algebraic formalism and a geometrical interpretation of image capture and color rendering.

Main Results

In a previous study [1] on RGBW sensor without infrared cutoff filter, we demonstrated the capability of accurate color rendering. However, the conclusions about its benefits in terms SNR were not clear. Here we start from the algebraic formalism of raw data acquisition: the raw data are the projections of the irradiance spectra on spectral sensitivities of the sensor. Thus, color-rendering problem can be reformulated as a back-projection from raw data to guess the initial irradiance, followed by its projection on a color space.

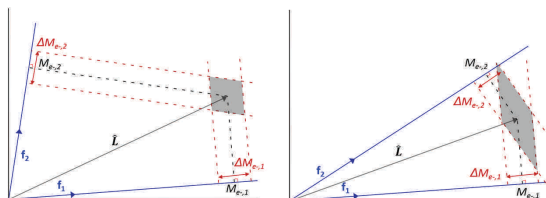


Fig. 1. Uncertainty of spectrum locus (grey area) due to noise in the case of weakly correlated channels (left) and highly correlated channels (right).

We introduce the covariant coordinates, given by irradiance projection on space defined by sensor sensitivities, and contravariant coordinates, used for the back-projection and irradiance estimation. Both coordinates are linked by the intrinsic

metric tensor of the space. So the color correction can be rewritten using this tensor applied on raw data. With this formalism, we define the angles between spectral sensitivities and show how they impact the propagation of noise from raw acquisition. As shown on Fig. 1, the lower the angle, the larger the uncertainty on the irradiance position.

Then, we validate this analysis on simulated images using our own multispectral dataset (see Fig. 2).

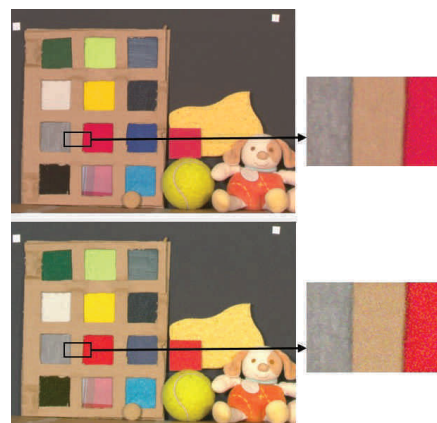


Fig. 2. Color image at saturation limit for RGB sensor (top) and RGBW without infrared cutoff filter (bottom)

Perspectives

The geometrical interpretation of color acquisition on image sensors is a useful tool: mathematical and geometrical models can guide physical optimizations of sensors according to the wanted applications. Moreover from signal point of view, the understanding of noise propagation can be used to design more effective algebraic operations for color correction and possibly denoising. By the way, even if this study was focused on color sensing, all geometrical considerations can be used in multi spectral imaging.

RELATED PUBLICATIONS:

- [1] J. Vaillant, A. Clouet, and D. Alleysson, Color correction matrix for sparse RGB-W image sensor without IR cutoff filter, Proc. SPIE 10677, 2018.
- [2] A. Clouet, J. Vaillant, et D. Alleysson, « Physical noise propagation in color image construction: a geometrical interpretation », Color and Imaging Conference, vol. 2019, n° 1, p. 375-380, oct. 2019, doi: 10.2352/issn.2169-2629.2019.27.67

A 5500fps 85GOPS/W 3D stacked BSI vision chip based on parallel in-focal-plane acquisition and processing

RESEARCH TOPIC:

Image sensor, 3D stacking, vision chip, in-focal-plane processing

AUTHORS:

L. Millet, S. Chevobbe*, C. Andriamisaina*, L. Benaissa, E. Deschaseaux, E. Beigne, K. Ben Chehida*, M. Lepecq*, M. Darouich*, F. Guellec, T. Dombek*, M. Duranton*.

*(LIST)

This work features a 2-layer 3D stacked back side illuminated vision chip for high speed visual inspection tasks with low latency. The circuit can analyze a 5500fps frame rate video flow by exploiting an image sensor with in-focal-plane pixel readout circuits combined to a programmable parallel computing array. It also allows heterogeneous parallel computations on up to 31×31 inter-pixels neighborhoods in a single chip.

SCIENTIFIC COLLABORATIONS: LIST

Context and Challenges

In many fields like automotive, industrial inspection or robotics, the growing needs for image analysis brings rising pressure on computing power and power consumption. Data communication also brings degraded latency in high speed applications.

Embedding computing capabilities in the image sensor is a way to reduce pressure on the external processing unit, while providing low latency features.

Main Results

In this work [1] we fabricated a vision chip for high speed analysis with low latency. Thanks to 3D stacked technologies, we successfully combined an image sensor to a massive processing matrix. The design is built around an elementary cell called macropixel (MPX), integrating a pixel array and ADC in the top tier, and dedicated processing elements and memories in the bottom tier as depicted in Fig.1.

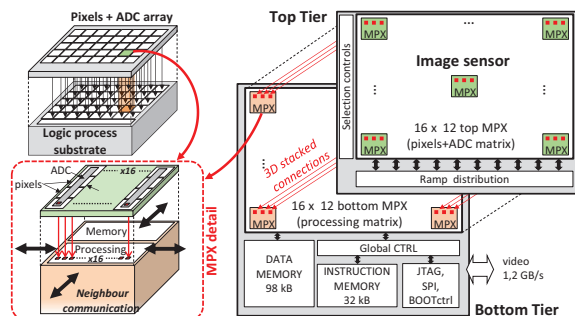


Figure 1 –Overview of the 2 layers 3D stacked vision chip

This approach brings at the same time a highly parallel communication between the two tier allowing a high framerate, and inter-pixel parallelism processing capabilities for low

latency applications.

Some examples are displayed in Fig.2, showing the high reconfigurable general purpose abilities of the vision chip. It features multistage pipeline computing, high-speed capture, high speed detection with low latency (triggers when falling balls are detected), local processing in specific image area, and dual resolution.

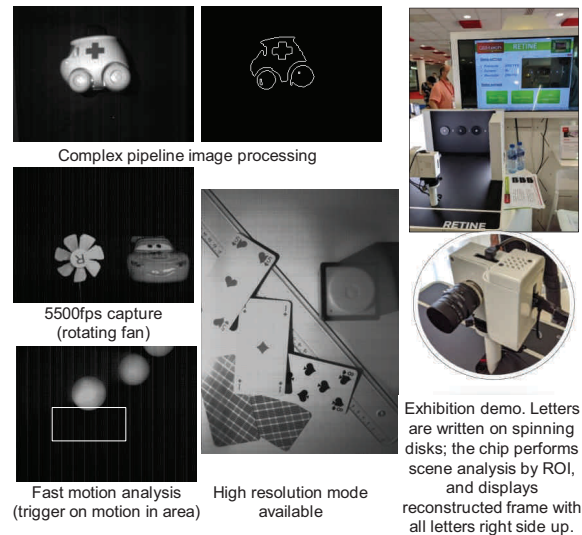


Figure 2 – High speed processing examples and demo

Perspectives

This chip demonstrates the benefits for near sensor computing applied to low latency applications. This concept will be expanded to increase the analysis options, and develop multi-sensor data fusion.

RELATED PUBLICATIONS:

[1] L. Millet, S. Chevobbe, C. Andriamisaina, L. Benaissa, E. Deschaseaux, E. Beigne, K. Ben Chehida, M. Lepecq, M. Darouich, F. Guellec, T. Dombek, M. Duranton, "A 5500-frames/s 85-GOPS/W 3-D Stacked BSI Vision Chip Based on Parallel In-Focal-Plane Acquisition and Processing", on IEEE Journal of Solid State Circuits, Vol.54, No 4, Apr. 2019

Compressive Image sensor based on hardware-friendly random modulations & permutations for streamed image compression and classification

RESEARCH TOPIC:

CMOS Image Sensor, Machine Learning, Compressive Sensing

AUTHORS:

Wissam Benjilali, William Guicquero and Gilles Sicard

This work focuses on a new compressive sensing acquisition scheme being well adapted for highly constrained hardware implementations. The proposed scheme [1] is designed to meet both theoretical (i.e., Restricted Isometry Property) and hardware requirements (i.e., power consumption and silicon footprint). This scheme is highly suitable for image sensors applications addressing both image rendering and embedded decision-making tasks. It led to a compact CMOS Image Sensor (CIS) architecture tentative design [2] enabling embedded object recognition. This architecture takes advantage of a low footprint pseudo-random data mixing circuit and a first order incremental Sigma-Delta Analog to Digital Converter (ADC) to directly extract compressed features.

SCIENTIFIC COLLABORATIONS: Laurent Jacques, ISPGROUP, ICTEAM/ELEN, UCLouvain, Louvain-la-Neuve, Belgium.

Context and Challenges

The last decade has testified a deep theoretical study of Compressive Sensing (CS) for both signal recovery and decision making problems. Indeed, CS has emerged as a hardware-friendly enabler. On one hand, reconstructing a signal from its CS measurements generally requires a complex iterative algorithm. But on the other hand, recent theoretical results show that signal processing can be directly performed in the compressed domain, for instance for machine learning.

Main Results

This work proposes a new CS scheme providing more independent measurements by extending bloc-based measurement supports. It is mathematically defined as a combination of random modulations with random permutation matrices. Fig. 1 exhibits a schematic description of a possible CMOS image sensor that would embed such on-the-fly data compression, taking advantage of an incremental Sigma-Delta ADC to perform CS. In addition, thanks to a compact Digital Signal Processor (DSP), this architecture enables basic decision-making such as single scale image classification.

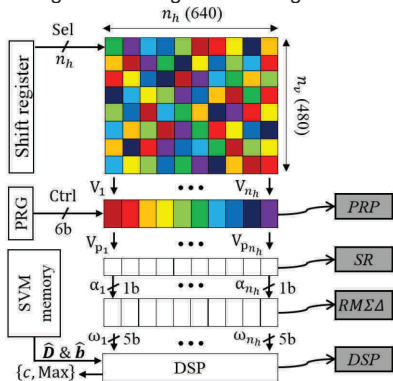


Fig. 1. Schematic description of the image sensor architecture.

The efficiency of this architecture and its sensing scheme itself has been quantified for both image rendering applications (cf. Fig. 2) and image classification (cf. Table I).



Fig. 2. Example of image reconstructions from compressed measurements, for a compression ratio of ~15%.

It exhibits impressive results compared to state-of-the-art in terms of image reconstruction even at a 0.2% compression ratio. It also demonstrates good performances for extracting relevant image features as reported in Table I, where the classification accuracy from CS measurements is higher than processing raw data.

RGB Bayer without CS	CS - SOTA (Rademacher)	CS - our sensing scheme (theo.)	CS - our sensing scheme (implem.)
91.6% (~300k)	87.8% (~600)	93.4% (~600)	93.2% (~600)

Table I. Classification accuracy results for various setups.

Perspectives

All the results are for the moment derived from high-level simulations; next step will be the imager design to confirm the validity of the approach with silicon based tests. In particular, we want to demonstrate the improvements in terms of power consumption of the entire system for low-power inference tasks.

RELATED PUBLICATIONS:

- [1] W. Benjilali, W. Guicquero, L. Jacques, and G. Sicard, « Hardware-Friendly Compressive Imaging Based on Random Modulations & Permutations for Image Acquisition and Classification », in IEEE International Conference on Image Processing, 2019.
- [2] W. Benjilali, W. Guicquero, L. Jacques, and G. Sicard, « An Analog-to-Information VGA Image Sensor Architecture for Support Vector Machine on Compressive Measurements », in IEEE International Symposium on Circuits and Systems, 2019.

Smart imagers modeling and optimization framework for embedded AI applications

RESEARCH TOPIC:

Smart imagers, behavioral simulation, spiking imagers, embedded artificial intelligence

AUTHORS:

Luis Angel Cubero Montealegre, Arnaud Peizerat, Dominique Morche, Gilles Sicard

This work presents a framework for behavioral simulations of smart imagers with hardware and power constraints. The objective is to compare innovative imaging systems that would be composed of a specific image sensor and a dedicated image processing. For that purpose, a versatile imager model is presented and applied to a time-to-first-spike imager associated with two types of neural networks. Image classification is targeted to assess the system performance, namely the classification accuracy and data throughput. Simulation results depict/show the impact of different key-parameters helping in the choice of the final imaging system architecture.

SCIENTIFIC COLLABORATIONS:

Context and Challenges

Artificial intelligence (AI) algorithms, such as convolutional neural networks (CNNs), can be used for image classification within 1000 categories. However, embedded device design requires to take into account hardware and power constraints, besides the performance of the AI algorithm. As a consequence, embedded AI architectures exhibit a trade-off between AI's performance and hardware/power limitations. In the computer vision field, this problem has been addressed with different approaches. For instance, the signal processing task could be distributed among the digital and analog domains for face detection and identification. Also, non-conventional and event-based schemes like "time to first spike (TTFS)" imagers, and the "time based CMOS dynamic vision and image sensor (ATIS)", have been exploited and adapted to specific application scenarios. For example, an extension of a TTFS imager, with an image compression technique has been proposed and reduces the events related data throughput. Another example reported an ATIS based system for object tracking applications.

Even though new ideas could improve further embedded AI's performance, proof-of-concept circuits are costly to be fabricated and tested. Then, having a simulation tool that enables characterizing performances from different (standard or not) imager types may be critical. Previous efforts have been done for modeling and simulating analog or mixed signal architectures, in such a way that lower level models from complex sub-blocks can be used in higher level simulations. Nevertheless, computer vision AI applications carry out (pre) processing steps that require to be tested and verified all together. Pre-processing stages may be linked to the analog/mixed-signal (A/MS) imaging system, and may have an impact on the further all-digital processing stages. This work proposes a framework for behavioral simulations of the whole signal processing chain: from image acquisition to the AI's output. Overall features of this imaging system can be extracted as a function of its parameters (e.g. classification accuracy vs. ADC resolution of the imager). Such a tool would boost

research and development of embedded AI on smart imagers. Lower level device features (e.g. delays, noise, mismatch, etc.) can be taken into account in further works. For said purposes, a model which tries to generalize smart imagers in a modular fashion is presented.

Main Results

A framework for behavioral simulations of smart imagers was developed (Fig. 1). It is intended to facilitate high level comparison and characterization for (non) standard imager architectures, and within the context of AI applications. One general and modular imager model was proposed. As an example, it was reduced to the case of a specific adaptation of a Time-to-first-spike imager, reflecting that classification accuracy on the MNIST dataset kept over 90 % for a block of size (2, 2). The trade-off between data throughput and classification performance has been illustrated in the paper.

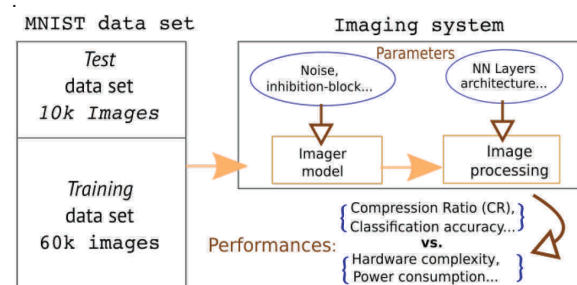


Fig. 1. Simulation framework block diagram

Perspectives

Further works could include specific (transient) models of A/MS electronic blocks. Then, computational complexity and data throughput could be mapped to power consumption or frame rates.

RELATED PUBLICATIONS:

[1] L.-A. Cubero Montealegre, A. Peizerat, D. Morche, G. Sicard, "Smart imagers modeling and optimization framework for embedded AI applications", 15th Conference on PhD Research in Microelectronics and Electronics (PRIME), Lausanne, Switzerland, July 15-18, 2019.

Near sensor decision making via compressed measurements for highly constrained hardware using hierarchical machine learning techniques

RESEARCH TOPIC:

CMOS Image Sensor, Machine Learning, Compressive Sensing

AUTHORS:

Wissam Benjilali, William Guicquero and Gilles Sicard

The motivation of this work is to demonstrate the interest of using Machine Learning based inference on Compressive Sensing (CS) measurements. The article [1] presents a comparative study on various learning and inference strategies using compressed measurements. For each proposed technique, we present and compare three approaches to perform near-sensor decision making. Based on the outcomes of [1], the article [2] explores hierarchical clustering methods to learn a hierarchical multi-class classifier directly on compressed measurements. Our results show that CS can relevantly be combined with a hierarchical inference to relax hardware requirements to its minimum, regarding both digital activity (i.e. number of MACs) and embedded memory needs.

SCIENTIFIC COLLABORATIONS: Laurent Jacques, ISPGROUP, ICTEAM/ELEN, UCLouvain, Louvain-la-Neuve, Belgium.

Context and Challenges

One current trend in embedded systems consists in developing computational-friendly, always-on decision-making enablers. To this goal, smart sensor tends to take advantage of recent advances in signal acquisition schemes and inference strategies, dedicated to low-power systems. Moreover, the design of this kind of information-retrieval signal processing architectures has to deal with on-chip constraints related to the processed data dimensionality and algorithms complexity. To tackle these two points at the same time, hierarchical strategies on Compressive Sensing based measurements seems a relevant, joint-design approach to limit both overall memory needs and dynamic power consumption issues.

Main Results

The article [2] introduced new methods to construct the tree to train a multiclass hierarchical linear classifier (as a binary decision tree) minimizing therefore the number of decision nodes required to pass during the inference stage. Working on Compressive Sensing measurements, it enables a large reduction of the algorithmic complexity as reported In Table I.

Learning	Memory	Computing
One-vs.-all	NC	$\mathcal{O}(NC)$
One-vs.-one	$NC(C-1)/2$	$\mathcal{O}(NC(C-1)/2)$
Hierarchical	$N(C-1)$	$\mathcal{O}(N \log_2 C)$
Hierarchical+CS	$M(C-1)$	$\mathcal{O}(M \log_2 C)$

Table I. Algorithmic complexity study.

In this Table I we compare the complexity of 4 approaches for C-class linear-SVM like classifiers. First, the commonly used "one-versus-all" strategy that consists in learning a single projection vector by class, secondly the "one-versus-one" (more rarely used) that outcomes a set of projection vectors where each is associated to a pair of classes, then "Hierarchical" that operates the classification using iterative decisions. In addition, Compressive Sensing here used as a dimensional reduction operator based on a randomly generated projection matrix acts

on limiting the size of the data (here denoted N) by compressing it to a smaller size (here denoted M such that $M \ll N$).

[2] also reports three clustering methods used to construct balanced clusters at each node thus reducing the depth of the decision tree in order to lower hardware requirements as minimum as possible. A binary Support Vector Machine (SVM) classifier is then used to learn 2-class separating hyperplanes on Compressive Sensing measurements at each node of the hierarchical tree. Table II shows simulation results for two classification databases (AT&T and COIL-100) in function of the clustering method used for training the decision tree (Sequential K-means, SVM-based or PCA-based). The reported accuracy demonstrates an acceptable reduction of performance with respect to the reduction of the overall complexity even while combined with a compression ratio of 25%.

		Linear SVM		Hierarchical SVM (our work)	
		One-vs.-one	One-vs.-all	Seq. K-means	SVM-based clustering
Accuracy (%)	w/o CS	98.3	95.8	93.1	95.1
	w/ CS	97.8	93.7	87.3	92.1
#SVMs		496	32	5	5

Table II. Classification accuracy results for our three balanced clustering methods (binary decision tree of depth 5) on 32 extracted classes of COIL-100 database.

Perspectives

Simulation results based on two simple databases show the great interest of our proposed approach in terms of hardware requirements (computational complexity and memory access needs) with an acceptable impact on the classification accuracy. In addition, when combined with CS, the overall memory and on-chip MAC operation needs can even be lowered. It demonstrates that low power hardware constrained decision-making algorithms can fully take advantage of a hierarchical learning approach combined with CS if the classification accuracy doesn't require to be that high (e.g., low-power sensing nodes). In terms of perspectives, in future developments we will extend our hierarchical approach from basic linear classifiers to non-linear Neural Networks, keeping in mind Hardware-related limitations (i.e., small NN topologies).

RELATED PUBLICATIONS:

- [1] W. Benjilali, W. Guicquero, L. Jacques, and G. Sicard, « Near Sensor Decision Making via Compressed Measurements for Highly Constrained Hardware », in IEEE Asilomar Conference on Signals, Systems and Computers, 2019.
- [2] W. Benjilali, W. Guicquero, L. Jacques, and G. Sicard, « Exploring Hierarchical Machine Learning for Hardware-Limited Multi-Class Inference on Compressed Measurements », in IEEE International Symposium on Circuits and Systems, 2019.



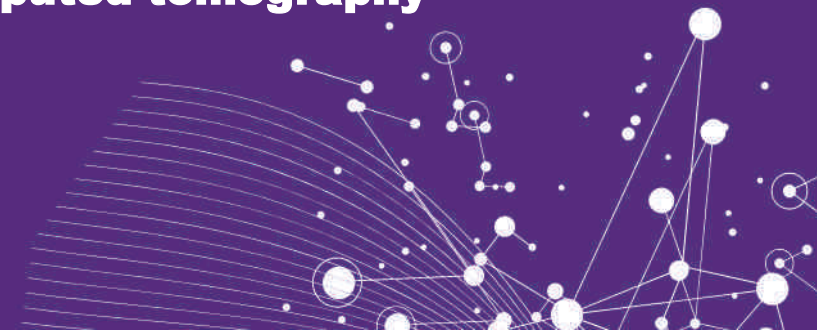


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O4

X RAY IMAGING

- **Perovskites for medical X-ray radiography**
- **Sensitive energy-resolved CdZnTe detectors with improved angular resolution**
- **Fast algorithm for image reconstruction in computed tomography**



Perovskite as new conversion material for medical X-ray imaging

RESEARCH TOPIC:

X-ray direct detection, medical radiography, perovskite

AUTHORS:

E. Gros-Daillon, O. Baussens, J.M. Verilhac (Liten), S. Amari (Liten), J. Zaccaro (CNRS), A. Ibanez (CNRS), L. Hirsch (CNRS),

A new X-ray to charge conversion layer based on hybrid perovskite is studied for medical X-ray radiography. A solution process compatible with large area elaboration has been developed and enabled to produce thick methylammonium tribromide single crystals. Chromium contact were carefully selected thanks to their chemical stability with the perovskite surface. The charge carrier transport properties were measured by laser time of flight and the electric field continuity was confirmed along the sample thickness using X-ray irradiation from the sample side. The sensitivity measured under X-ray in medical condition is around $3 \mu\text{C.mGy}^{-1}.\text{cm}^{-2}$ which is three time higher than commercial indirect imagers for radiography.

SCIENTIFIC COLLABORATIONS: CEA-Liten, CNRS, common lab between CEA and Trixell

Context and Challenges

Medical radiography is the most used medical imaging modality. State-of-the-art X-ray flat panels are based on a two-steps X-ray to charges conversion process by a scintillator layer and an array of photodiodes on an amorphous silicon TFT backplane. Despite remarkable performances, it is still a challenge to further enhance diagnostic while reducing the x-ray dose for demanding applications such as cardio vascular disease diagnostic and treatment. A higher sensitivity coupled with a better spatial resolution will enable better imaging of the moving stents, as it is important for clinicians to clearly observe how the stent's scaffold unfolds into the occluded vessel. Moreover, recent experience of Covid-19 showed the importance of obtaining excellent image quality bedside chest radiography, performed directly in the emergency ward in patients contaminated by the virus, for selection of severe cases who must be hospitalized.

To reach this goal, a new semiconductor is studied by CEA/Leti and CEA/Liten in order to convert directly the incoming X-rays into electric charges in a one-step process. The semi-conducting materials we have selected belong to the emerging hybrid organic-inorganic perovskite family that is actively studied for photovoltaic applications. Indeed, hybrid perovskites present remarkable optoelectronic properties (high charge carrier mobility, long charge carrier lifetime, large diffusion lengths and adequate X-ray absorption) favorable for high efficiency direct X-ray conversion.

Main Results

We investigated methylammonium lead tribromide (MAPbBr_3) as candidate for X-ray detection. A process compatible with low cost and large area processing has been developed in solution and at low temperature. A modified seeded inverse temperature crystallization method allowed to routinely grow thick single crystals with minimized internal stress and density of structural defects [1].

The key performances for X-ray imaging lie in a low dark current density and a good charge carrier transport properties. In this ionic crystal, ion can migrate (mainly bromine vacancy $\text{V}_{\text{Br}^{+}}$) under the intense applied electric field. Halide vacancies

accumulate near the negative-biased contact and could react with some electrode materials. Thermally evaporated chromium has been selected as a material that spontaneously oxidizes during sample preparation leading to stable devices (fig. 1). This leads to a reduced hysteresis effects and a dark current of $10\text{-}40 \text{ nA/mm}^2 @50\text{V/mm}$.

The charge carrier transport properties were measured by laser time of flight. A holes' mobility of $13 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ was measured and a holes' lifetime of a few tenth of μs is estimated [2]. The continuity of the charge carrier transport along the 2 mm thickness of the samples was confirmed by focused X-ray illumination along the edge of the samples (fig. 2), leading to a high X-ray to electron conversion rate of $3 \mu\text{C.mGy}^{-1}.\text{cm}^{-2}$.

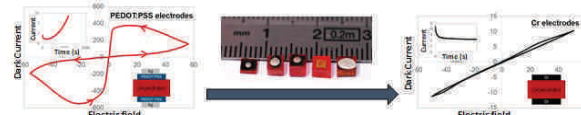


Fig. 1. Device stabilization thanks to electrode engineering.

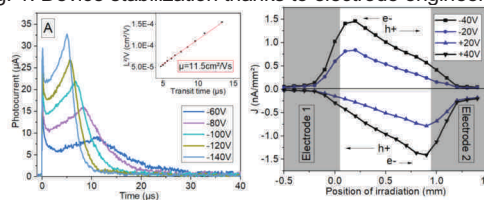


Fig. 2. Left: mobility measurement by laser time of flight. Right: X-ray photocurrent with respect to the depth.

Perspectives

Methylammonium lead tribromide thick single crystals were grown and stable devices were fabricated and evaluated under X-ray irradiation. The charge carrier transport properties were measured and the electric field continuity was confirmed using X-ray edge irradiation. The next step will be to further decrease the dark current in order to optimize the signal to noise ratio, and to transfer these performances to a pixelated large area imager [3].

RELATED PUBLICATIONS:

- [1] Optimization of the growth conditions for high quality $\text{CH}_3\text{NH}_3\text{PbBr}_3$ hybrid perovskite single crystals, S. Amari, J. M. Verilhac, E. Gros D'Aillon, A. Ibanez, et J. Zaccaro, Cryst. Growth Des., janv. 2020, <https://doi.org/10.1021/acs.cgd.9b01429>
- [2] An insight into the charge carriers transport properties and electric field distribution of $\text{CH}_3\text{NH}_3\text{PbBr}_3$ thick single crystals, O. Baussens, L. Maturana, S. Amari, J. Zaccaro, J.M. Verilhac, L. Hirsch, E. Gros-Daillon, Appl. Phys. Lett. 117, 041904 (2020), <https://doi.org/10.1063/5.0011713>.
- [3] <https://peroxis-project.eu/>

Combining spatially- and energy-resolved CdZnTe detectors with multiplexed collimations to improve performance of X-ray diffraction systems for baggage scanning

RESEARCH TOPIC:

X-ray diffraction imaging, explosives detection, baggage screening, CdZnTe spectrometric detectors, sub-pixelation

AUTHORS:

J. Tabary, M-C. Gentet, O. Monnet, C. Paulus, G. Montémont

Energy Dispersive X-ray Diffraction (EDXRD) is proven to be an effective technique for baggage screening, as it can reveal inter- and intramolecular structural information of any solid (mostly polycrystalline) or liquid substances. However, this technique suffers from a lack of sensitivity.

Using its own developed CdZnTe based energy resolved detectors, the CEA-LETI implemented an EDXRD system using a multiplexed secondary collimation. The sensitivity is more than four times better compared to a standard parallel collimation.

This article [1] presents how this system architecture, combined with specific iterative inversion algorithms, manages to reconstruct the diffraction signatures of materials, even when they are close to each other. Material discrimination performance limits are explored for several objects scenarios and various levels of photon statistics.

Context and Challenges

Detecting hidden threats in baggage is a crucial task for aviation safety. Conventional systems used to control baggage at airports are based on dual or multi-energy transmission imaging. While this approach is well-established and yields high-resolution imagery, its material specificity is limited, still leading to a high number of false alarms. Thus, other techniques are proposed, such as Energy Dispersive X-ray Diffraction (EDXRD), which are very more specific by revealing the molecular composition and structure of any solid or liquid substances.

However, the EDXRD technique requires fixing the scattering angle to few degrees with very thick collimations, which induces lack of sensitivity. It is then a question of proposing technological, architectural and algorithmic solutions to improve and find the best compromise between spatial resolution, power of discrimination and inspection speed.

Main Results

The CEA-LETI has developed 2D CdZnTe based energy resolved detectors with very high-energy resolution of about 3% at 140 keV, which makes them particularly relevant for use in XRD systems. Moreover, thanks to specific detector-level signal processing called subpixelation, those detectors also present very high spatial resolution [2], which can significantly improve angular resolution in EDXRD systems and therefore sensitivity if combined with opened collimations.

Thus, based on such a module called HiSPECT, we implemented an EDXRD system using a slight multiplexed secondary collimation, in which each physical pixel inspects the object at 4 or 5 different points. This architecture induces a sensitivity gain of more than 4 compared to a classical collimation without degradation of the angular resolution (5.7 % thanks to subpixelation, vs 10.8% without). In order to solve the ill-posed problem related to the multiplexed collimation, some specific iterative inversion algorithms [3] have been developed to reconstruct the diffraction signatures of the materials, even when they are close together as inside a baggage.

The experimental results we obtained on different representative

bi-material objects showed that with our multiplexed collimation, discrimination between harmless and dangerous materials is still possible even at low fluxes.

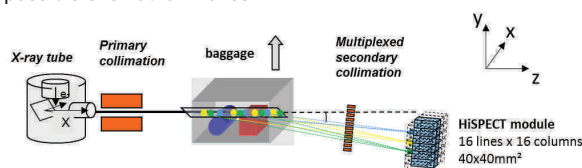


Fig. 1. Schematic of the XRD imaging system, designed with a multiplexed secondary collimation and using the HiSPECT module developed at CEA-LETI.

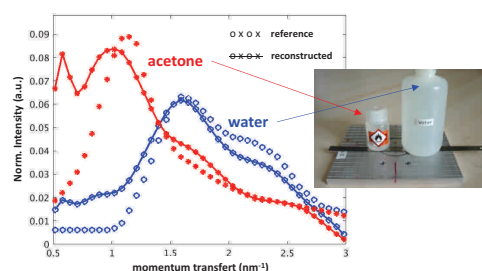


Fig. 2. Reconstructed diffraction signatures of acetone and water, compared to the ground truth.

Perspectives

Nevertheless, it appears that the reconstruction of diffraction signatures along the spatial direction is more difficult. However, the addition of an a priori on the object positions (obtained for instance thanks to a previously acquired radiograph) solves these problems and drastically enhances the reconstruction and classification processes. This confirms that diffraction and transmission are rather complementary, which prompts us to think for the future of systems combining both techniques.

RELATED PUBLICATIONS:

- [1] Tabary, J., Gentet, M-C., Monnet, O., Paulus, C., Montémont G., " Combining spatially- and energy-resolved CdZnTe detectors with multiplexed collimations to improve performance of X-ray diffraction systems for baggage scanning, " Proc. SPIE ADIX IV 10999, (2019).
- [2] Montémont, G., Lux, S., Monnet, O., Stanchina, S., Verger, L. "Studying spatial resolution of CZT detectors using sub-pixel positioning for SPECT," IEEE Transactions on Nuclear Science 61, 2559-2565 (2014).
- [3] Barbes, D., Tabary, J., Paulus, C., Hazemann, J-L., Verger, L. "Material-specific imaging system using energy-dispersive X-ray diffraction and spatially resolved CdZnTe detectors with potential application in breast imaging," Nuclear Instruments and Methods in Physics Research A 848, 91–98 (2017).

A fast gradient-based algorithm for image reconstruction in inverse geometry computed tomography architecture with sparse distributed sources

RESEARCH TOPIC:

X-ray Computed Tomography, inverse geometry, iterative image reconstruction, sparse distributed sources

AUTHORS:

Frédéric Jolivet, Clarisse Fournier, Andréa Brambilla

Multi-source inverse geometry CT (MS-IGCT) system consists in using several X-ray sources and a small detector to acquire several partial sinograms of the object. One expected benefit over a conventional Cone Beam Computed Tomography system is to improve image quality by reducing scattered radiation. Another advantage is the possibility to use smaller detector, but with advanced functionality, such as energy resolved Photon Counting Detectors. The counterpart is the need to develop dedicated reconstruction methods capable of handling unconventional geometry. We proposed an accelerated proximal algorithm for MS-IGCT and we demonstrated the performance of the method when we reduce significantly the size of the detector and a limited number of sources. We also implemented an experimental bench to acquire data in inverse geometry conditions and to show qualitative improvement of the reconstruction algorithm compared to classical approaches.

Context and Challenges

The emergence of new multiple and distributed X-ray sources opens up new perspectives to innovative system concepts in X-ray radiography and computed tomography (CT). Multi-source inverse geometry CT system (MS-IGCT) consists in using several sources and a small detector. For technological, financial and medical reasons the reduction of the number of sources and the reduction of the detector size are interesting but induce to solve an ill-posed and ill-conditioned problem. We proposed a regularized iterative algorithm which is able to reconstruct the object volume from partial sinograms acquired with an optimized MS-IGCT system.

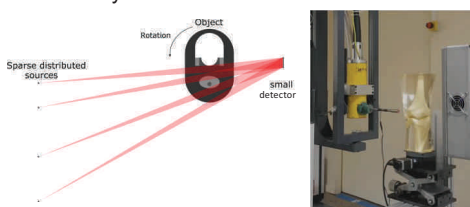


Fig. 1. Left: MS-IGCT architecture with a few distributed sources and a small detector. Right: setup with mobile X-ray source used for experimental validation

Main Results

We consider a linear model for the sinogram d_p acquired when the p -th source is active. Assuming a Gaussian white noise and some *a priori* on the volume x , the *Maximum A Posteriori* estimation is the solution $\hat{x}$ of the following problem:

$$\hat{x} = \underset{x \geq 0}{\operatorname{argmin}} \frac{1}{2} \sum_{p=1}^{N_p} \|A_p x - d_p\|_{W_p}^2 + \lambda TV_{iso}(x)$$

Positivity constraint
(physical prior on the attenuation)
Data fidelity term
Regularization term
(Isotropic total variation)

where W_p is the inverse of the covariance matrix of the noise. To resolved the non-smooth constrained minimization problem, we propose an iterative reconstruction algorithm based on the

FISTA optimization strategy [1] and we compare our results on simulated and experimental data with two classical approaches.

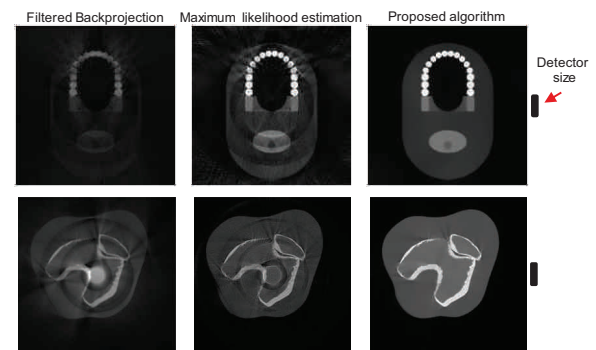


Fig. 2. Top: simulated results. Bottom: experimental results. 4 distributed sources

Reconstruction with the proposed algorithm presents a better signal-noise ratio and is more quantitative. The comparison between the maximum likelihood estimation and our proposed algorithm shows the importance of the regularization term. These are promising results because it is possible to reduce significantly the detector size (compared to conventional CBCT architecture), while using sparse distributed sources and a dedicated algorithm.

Perspectives

One perspective is to combine flat panel distributed X-ray sources with small advanced spectrometric detector to propose a new multi-energy inverse geometry tomography architecture. This geometry will benefit from the spectral information of the detector in terms of image quality, reduction of artefacts and quantification of biological tissues, while relaxing the constraint on the sensor size. First results obtained with noisy simulated data and new reconstruction algorithm [2] are promising but must be validated on experimental data.

RELATED PUBLICATIONS:

- [1] F. Jolivet, C. Fournier, and A. Brambilla, "A fast gradient-based algorithm for image reconstruction in inverse geometry ct architecture with sparse distributed sources," in 15th International Meeting on Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine, vol. 11072. International Society for Optics and Photonics, 2019, p. 110721N
- [2] F. Jolivet, C. Fournier, J. Lesaint and A. Brambilla, "A one-step algorithm for spectral CT with an application on multi-source inverse geometry," in 6th International Conference on Image Formation in X-Ray Computed Tomography, August 2020.



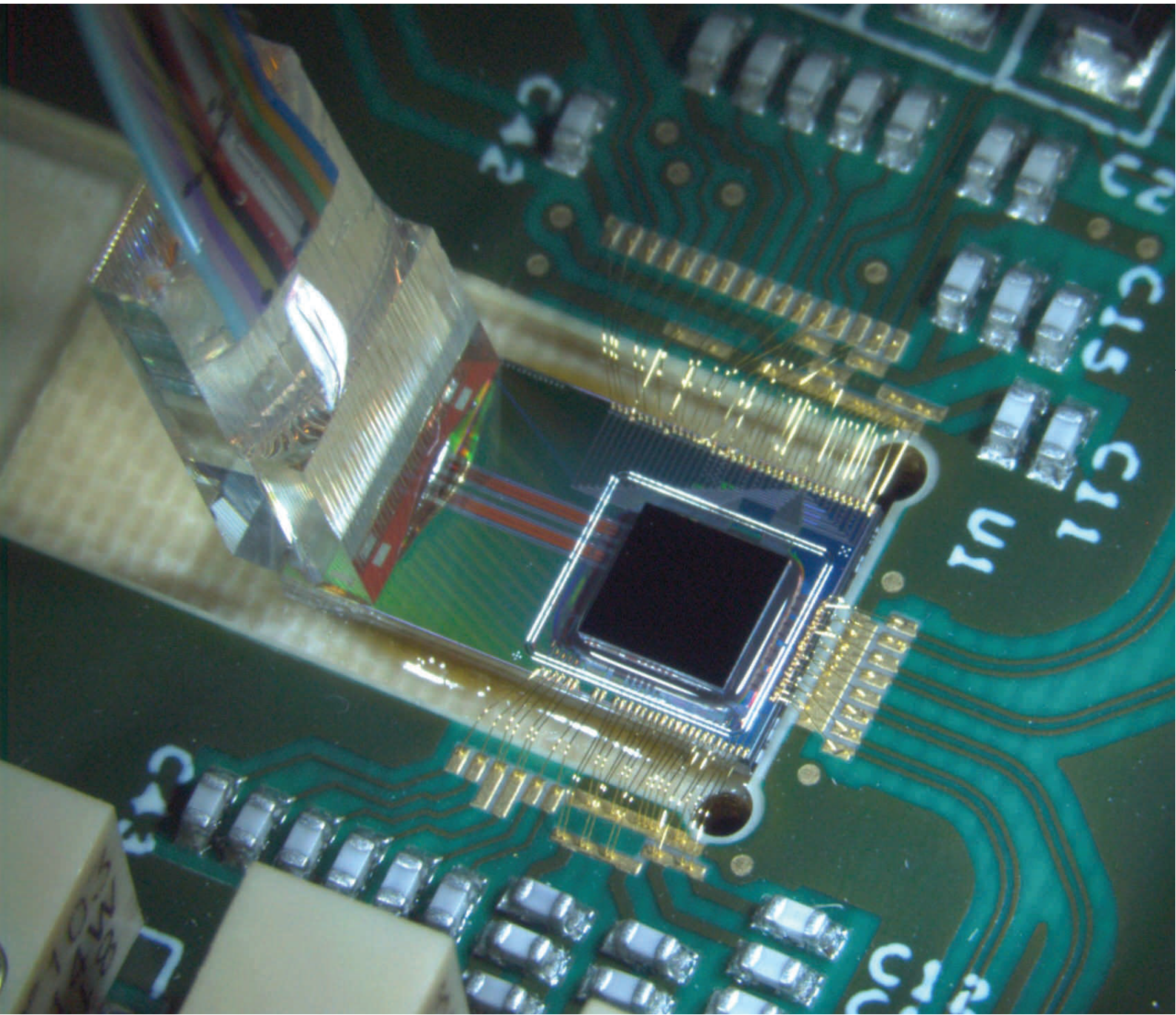
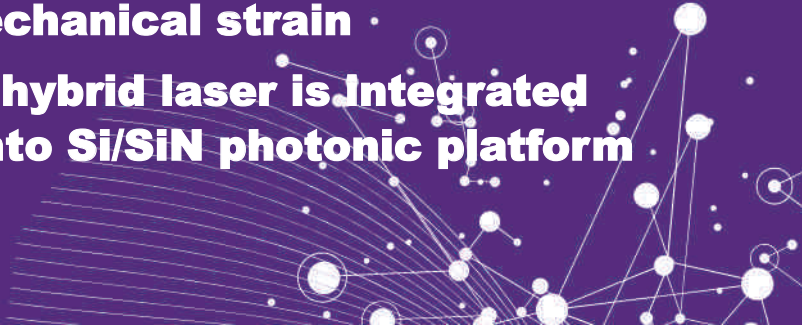


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O5

SILICON PHOTONICS

- **Technology for ultra low loss Si waveguides becomes mature**
 - **Si photonics generates photon pairs for quantum information technology**
 - **Ultra low loss SiN waveguides generate optical combs**
 - **Leti's Si photonics platform transits to immersion lithography**
 - **Mid-IR lasing in GeSn improved with extreme mechanical strain**
 - **III-V-on-Si hybrid laser is integrated back-side into Si/SiN photonic platform**
- 

Ultra-low loss silicon waveguides in a mature photonics platform

RESEARCH TOPIC:

Silicon photonics, process integration, waveguides, optical loss.

AUTHORS:

Q. Wilmart, S. Brisson, J.M. Hartmann (DPFT), A. Myko, K. Ribaud, D. Fowler, E. Pargon (LTM CNRS), S. Bernabé, B. Szlag.

We obtained state-of-the-art propagation losses in silicon sub-micrometric waveguides on a 200 mm CMOS compatible photonics platform. Thanks to a smoothing annealing, the loss reduction is spectacular - down to 0.1 dB/cm - while the performances of the main passive and active building blocks of the photonics platform are not deteriorated. This breakthrough will have a major impact on power consumption of any photonic circuits with a gain of several dBs in transceiver circuits for optical communications. Furthermore, it is a key enabler for advanced applications such as optical quantum communication and computing.

IDENTIFIC COLLABORATIONS: LTM CNRS

Context and Challenges

The optical propagation loss of silicon waveguide is a major issue in silicon photonics where increasingly complex circuits with large numbers of components and long routing sections are required in many applications (Datacom, optical switches, LIDAR). The loss issue is even more critical in quantum photonics where ultra-low losses are required both for photon pair generation using non-linear effects ([see next article](#)) and for single photon manipulation and routing.

Main Results

In guided optics, the main source of optical losses is the sidewall roughness of the silicon waveguide. In collaboration with LTM-CNRS (as part of IRT nanoelec) we developed a H₂ thermal annealing leading to a smoothing of silicon at the atomic scale [1]. This new process step is inserted in our standard fabrication flow after the silicon patterning step [2]. The loss reduction is spectacular for all types of waveguides in both spectral bands of interest in photonics namely O (1310nm) and C (1550nm), as seen in Fig. 1. A wafer-level mapping of optical losses is shown in Fig. 2-a for a smoothed strip waveguide at 1310nm. The wafer median value is 1.1dB/cm, to be compared with 3.6dB/cm without smoothing. Electron microscopy cross sections of strip (and rib) smoothed waveguides are shown in Fig. 2 b (and c). The annealing results in slight shape changes only (rounded corners and slight sidewall slope). Therefore, the basic components of LETI's photonic library are still operational, even the most sensitive ones such as grating fiber couplers. Furthermore, active devices are annealing-resilient: the P-N junction which is used as a fast phase shifter in Mach Zehnder Modulators (MZM) is not impacted. Indeed, the main figure-of-merit for the MZM efficiency ($V_{\pi}L_{\pi}=1.5V.cm$) is unchanged while the device insertion loss is reduced by several dBs. Therefore, introducing the smoothing annealing in the mature photonics platform (3 Si etching levels, 6 doping levels, Ge photodiodes, heater and 2-level metallizations) leads to record-low losses without compromising devices performances nor requiring major changes in the process integration flow.

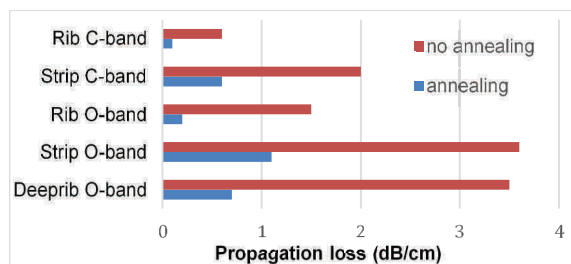


Fig. 1. Silicon waveguides propagation losses in the in O and C spectral bands with and without smoothing annealings.

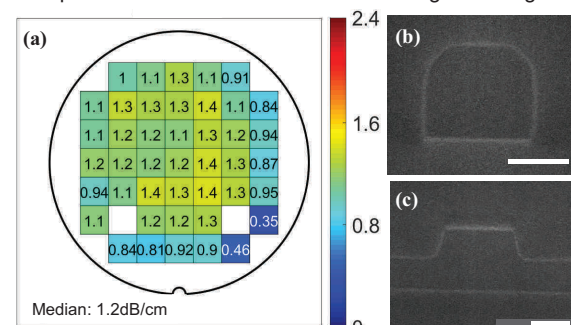


Fig. 2. (a) Wafer scale mapping of smoothed strip waveguide propagation losses at 1310nm (in dB/cm). (b) Cross section SEM images of smoothed strip and (c) rib waveguides (scale: white bar = 200nm).

Perspectives

The smoothing annealing is now implemented as a standard process step in the 200mm platform and is being developed for the 300mm platform. In collaboration with LTM-CNRS, new routes are explored to keep pushing the reduction of propagation losses, notably by working on the oxide encapsulation of silicon waveguides.

RELATED PUBLICATIONS:

- [1] C. Bellegarde E. Pargon, C. Sciancalepore, C. Petit-Etienne, V. Hugues, D. Robin-Brosse, J. Hartmann, P. Lyan, « Improvement of Sidewall Roughness of Submicron SOI Waveguides by Hydrogen Plasma and Annealing », IEEE Photonics Technol. Lett., vol. 30, no 7, p. 591-594, avr. 2018
- [2] Q. Wilmart, C. Bellegarde, C. Petit-Etienne, L. Youssef, J.-M. Hartmann, D. Fowler, S. Brisson, S.e Garcia, A. Myko, K. Ribaud, P. Grosse, B. Charbonnier, S. Bernabé, C. Sciancalepore, E. Pargon, B. Szlag « Ultra Low-Loss Silicon Waveguides for 200 mm Photonics Platform », in 2019 IEEE 16th International Conference on Group IV Photonics (GFP), 2019

Integrated source of photons pairs on silicon for quantum information technology

RESEARCH TOPIC:

Integrated quantum photonics, generation of quantum states of light.

AUTHORS:

S. Olivier, C. Sciancalepore, H. El Dirani, J.-M. Hartmann, C. Petit-Etienne (CNRS-LTM), E. Pargon (CNRS-LTM), F. Sabbatoli (Univ. Pavia), F. Garrisi (Univ. Pavia), M. Liscidini (Univ. Pavia), M. Galli (Univ. Pavia), D. Bajoni (Univ. Pavia)

To meet the requirements of emerging applications such as perfectly secure quantum communications or quantum computing, silicon photonics is a very attractive technology platform. We report on the development of an integrated source of time-energy entangled photon pairs generated by four-wave mixing in a high quality factor silicon ring resonator. The source features very good number purity and a high brightness with a generation rate of several MHz. Depending on the targeted application, the source can alternatively be used as a heralded source of single photons. This demonstration is a first step towards a fully integrated quantum photonics platform including high-speed manipulation circuits and superconducting single photon detectors.

SCIENTIFIC COLLABORATIONS : UNIVERSITY OF PAVIA

Context and Challenges

The field of quantum information technology concentrates a lot of research efforts worldwide. Single photons which feature excellent robustness against decoherence effects even at room temperature are ideal qubits for emerging applications such as perfectly secure quantum communications and can also be envisaged for quantum computing as an alternative to ultra-low temperature superconducting qubits. Such quantum information applications require a scalable, compact and low-cost technology for future widespread deployment. Silicon photonics is a very attractive technology platform for this purpose to implement several key functionalities such as photonic qubit generation, manipulation and detection on-chip.

In this report, we focus on the development of a bright and stable integrated source of time-energy entangled photon pairs on silicon.

Main Results

Silicon ring resonators are excellent candidates to generate quantum states of light by using four-wave mixing non-linear effect.

Silicon ring resonators coupled to an input/output waveguide were fabricated on CEA-Leti 8-inch platform, with careful optimization of lithography, etching and subsequent smoothening of waveguide walls to minimize scattering loss. The emission spectrum of a 100 μm radius ring resonator (700 nm waveguide width and 340 nm waveguide height) under resonant optical pumping at 1550 nm by a CW laser is shown in Figure 1a. It features multiple resonances of 5 pm width (corresponding to a high Q factor of 3×10^5) associated to signal and idler photon pairs distributed on each side of the pump wavelength. The non-linear resonance covers a 30 nm spectral range on each side of the pump.

Under weak optical pumping power, time-energy entangled pairs of single idler and signal photons can be obtained. This was verified using a Hanbury Brown and Twiss (HBT) experiment heralded by the idler photon, as sketched in Figure 1b. A pair of signal/idler photons is extracted from the full emission spectrum thanks to a narrow-band high-rejection DWDM filter. The signal photon is sent to a beam splitter with two detectors at the output, allowing to measure the 2nd order correlation function $g^{(2)}(\tau)$

where τ is the delay of the signal photons with respect to the herald. The recorded 2nd order correlation function for a pumping power of 163 μW is shown in Figure 1c. A clear dip can be seen for $\tau = 0$, which is the signature of the single photon nature of the idler with very good number purity.

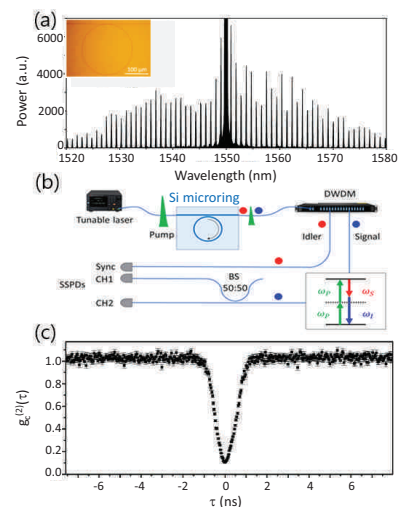


Fig. 1. (a) Emission spectrum of a silicon ring resonator under resonant CW optical pumping (b) Schematics of the HBT experiment to demonstrate emission by pairs. (c) 2nd order correlation function of the signal photons with respect to the herald.

Thanks to the high quality factor of the ring resonator, our source features a high brightness with a generation rate of several MHz. It can be used either as a source of time-energy entangled photon pairs or as a heralded source of single photons, the idler photons being the herald for the signal single photon emission.

Perspectives

This demonstration is a first step towards the development of a fully integrated quantum photonic platform on silicon, including also pump rejection filter, high-speed manipulation circuits and superconducting single photon detectors.

RELATED PUBLICATIONS:

- [1] H. El Dirani et al., "Low-loss silicon technology for high-Q bright quantum sources", Proceedings of the Group IV Photonics Conference (2019)
- [2] F. Sabbatoli et al., "A source of heralded single photon using high quality factor silicon ring resonators", Proceedings of the International Conference on Transparent Optical Networks (2019)

Ultra-high quality factor Si₃N₄ microresonators and optical comb sources

RESEARCH TOPIC:

Nonlinear optics, optical frequency combs, Kerr effect, ultra-low loss silicon nitride, UV generation, butt-coupling.

AUTHORS:

Q. Wilmart, H. El Dirani, S. Boust, F. Duport, L. Youssef, C. Petit-Etienne, S. Kerdiles, E. Pargon, F. Van Dijk, and C. Sciancalepore

We demonstrate the fabrication of ultralow-loss (ULL) Si₃N₄ waveguide (3dB/m) in the tight confinement regime. High quality microring resonators exhibit intrinsic quality factors approaching 10⁷ at 1550nm and give access to nonlinear phenomena with a low power threshold. By butt-coupling the Si₃N₄ photonic chip to a III-V DFB laser we obtain a 113nm-broad optical comb. We also demonstrate UV-light generation from infrared pumping. These results are either world first or in-line with the current state-of-the-art.

The ULL Si₃N₄ photonic platform offers exciting opportunities in some fields as various as LIDARs, optical communication and computation, metrology and quantum photonics.

SCIENTIFIC COLLABORATIONS: LTM-CNRS, III-V lab

Context and Challenges

A growing number of emerging applications in photonics will exploit nonlinear phenomena in integrated waveguides to generate frequency combs: fast and high-resolution LIDARs, neuromorphic circuits, optical clocks, multiplexed optical communications, photon pair generation for quantum communication and computing. For a long time, the generation of frequency comb by Kerr nonlinearity required high power and voluminous setups. Thanks to its significant nonlinear index and ultra-low optical loss (low refractive index and absence of 2-photon absorption) Si₃N₄ microring resonators display nonlinear effects at low threshold power.

The technological challenges consist of obtaining low-defect and stoichiometric Si₃N₄ (for high power damage threshold and low optical absorption) with relatively thick waveguides (for anomalous dispersion) and a low sidewall roughness (to minimize scattering-induced optical losses) while managing the high tensile stress of the Si₃N₄ film.

Main Results

The fabrication process was optimized to achieve ultra-low optical losses: 800nm-thick Si₃N₄ is deposited by a 2-step Low Pressure Chemical Vapor Deposition for film-stress management, the Si₃N₄ film is patterned by a tailored fluorocarbon dry etching, a multistep annealing smooths out the waveguide sidewalls and drives out the residual hydrogen (causing absorption at 1550nm) and the final multistep oxide deposition ensures a proper Si₃N₄ interface and a void free encapsulation. Thanks to this carefully optimized process flow, we obtain quality factors approaching 10⁷ and optical losses down to ~3dB/m [1] (see Fig. 1). Furthermore, this high quality waveguide is uniform on the 200mm wafer scale and show high power damage threshold (~ +40dBm injection power).

The high quality microring resonators are then exploited in the nonlinear regime: Ultraviolet light ($\lambda=392\text{nm}$) is generated through the interplay of $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear processes by pumping the ring resonance at $\lambda=1550\text{nm}$ [2]. In another experimental scheme, the Si₃N₄ chip is butt-coupled to a III-V

DFB laser chip with theoretical coupling loss ~1.1dB. The DFB pumping of the Si₃N₄ ring gives rise to an optical comb (by cascaded four wave mixing) with a 30dB bandwidth of 113nm and 120 longitudinal modes [3] (Fig. 2). This comb is one of the broadest ever measured for a microresonator directly pumped by a gain chip.

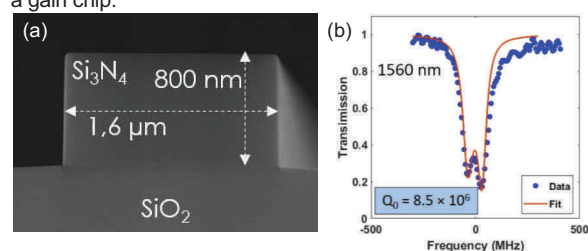


Fig. 1. (a) SEM cross section of the waveguide with vertical sidewalls. (b) Si₃N₄ ring resonance doublet measurement.

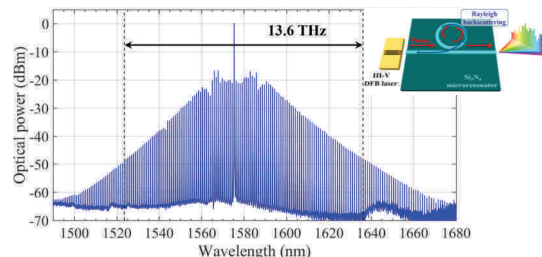


Fig. 2. Optical comb measurement. Inset: experimental setup.

Perspectives

These technological developments allowed us to catching up the state of the art in term of losses. The next important step is to include ULL Si₃N₄ within a full silicon photonics platform featuring silicon waveguides and active devices. This will give access to a whole new set of exciting applications ranging from sensors, communications and computing to quantum photonics.

RELATED PUBLICATIONS:

- [1] H. El Dirani, C. Petit-Etienne, L. Youssef, S. Kerdiles, P. Grosse, C. Monat, E. Pargon and C. Sciancalepore "Ultralow-loss tightly confining Si₃N₄ waveguides and high-Q microresonators" *Opt. Express* 27, 30726-30740 (2019)
- [2] H. El Dirani, A. N. Kamel, M. Casale, S. Kerdiles, C. Monat, X. Letartre, C. Socquet-Clerc, M. Pu, L. K. Oxenløwe, K. Yvind, J. Lægsgaard, and C. Sciancalepore, "UV-Light Generation In Silicon Nitride Resonators Pumped At Telecom Wavelengths" in *IEEE 16th International Conference on Group IV Photonics (GFP)*, 2019.
- [3] S. Boust, H. El Dirani, L. Youssef, Y. Robert, A. Larue, C. Petit-Etienne, E. Vinet, S. Kerdiles, E. Pargon, M. Faugeron, M. Vallet, F. Duport, C. Sciancalepore, F. Van Dijk, "Microcomb source based on InP DFB / Si₃N₄ microring butt-coupling", *Journal of Lightwave Technology* (2020).

Transition to Immersion lithography for the LETI Si Photonics platform

RESEARCH TOPIC:

Si Photonics fabrication, immersion lithography and OPC*

AUTHORS:

C. Dupré, D. Fowler, L. Adelmini, E. Arnoux (DPFT), E. Guyez (DPFT), C. Lapeyre (DPFT), A. Fay (DPFT), L. Perraud (DPFT), P. Brianceau (DPFT), A. Myko, B. Szélag

The 300mm Si Photonics platform at LETI now takes advantage of the immersion lithography tool, enabling reduced dimensional variations across a wafer and between wafers, increasing yield. Lower waveguide propagation losses have also been measured thanks to the higher spatial resolution available using immersion lithography (from 1.7 to 0.9dB/cm @1310nm for rib waveguides). The small feature sizes allowed by the tool in conjunction with OPC, offer new design opportunities, however the OPC parameters must be optimized to account for the wide variety of curvilinear forms found in Si photonics.

SCIENTIFIC COLLABORATIONS: C2N-CNRS

Context and Challenges

Photonic integrated circuits using CMOS technology platforms are key components for low-cost, high data-rate transceivers. The device fabrication yield within a single wafer and from wafer to wafer is crucial in order to provide reliable, high performance products. Si Photonics benefits from the strengths of the microelectronic industry in terms of tools and process control. The introduction of immersion lithography for Si Photonics enables to go a step forward in terms of performance and reproducibility. In addition, the combination of Immersion lithography and OPC allows access to components with dimensions below 100nm opening new design opportunities.

Main Results

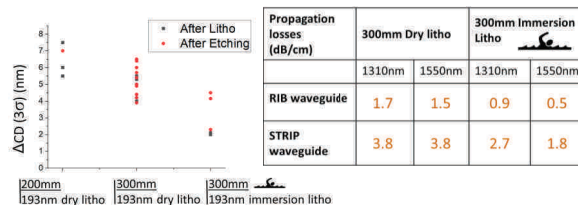


Fig. 1. (left) The critical dimension variation ΔCD is reduced going from a 200mm to a 300mm fabrication line and is further improved with immersion lithography. (right) Immersion lithography reduces propagation losses

Standard Si photonics technology has been fabricated using immersion lithography and OPC and compared to the reference 200mm line based on dry lithography. The CD variation is reduced from the 200mm to 300mm platform, and again from dry to immersion lithography (Fig. 1, left). The enhanced control of dimensions will directly improve device yields within and across wafers. For example, not only can fibre grating couplers be made more efficient, but also more spectrally homogenous. The resonant frequency of microring resonators shows significantly less variation, reducing the requirement of thermal trimming (Horikawa,

10.1109/JSTQE.2018.2819893). Waveguide propagation losses are reduced from dry to immersion lithography as seen in Fig. 1, right. An additional smoothing treatment has also shown further propagation losses reduction, from 0.9 to 0.6dB/cm for RIB waveguides at 1310nm.

Advanced designs have been fabricated taking advantage of the small dimensions allowed. Figure 2 illustrates 1D and 2D grating couplers fabricated using this technology. 1D grating coupler losses were measured at 1.6dB, showing a 0.4dB improvement compared to the 200mm fabrication line. Significant further improvements are expected with continuing OPC development.

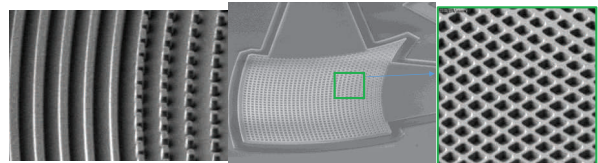


Fig. 2. 1D and 2D grating couplers

In comparison to microelectronics, Si Photonics devices exhibit (1) curved or non-'Manhattan' forms and (2) a high variety of shapes on the same mask. Depending on the desired structure, OPC* for Si Photonics may need to be device-specific. OPC consists of (1) manhattanization of the curved photonic shapes and (2) appropriate edge displacements to ensure the fabricated device is faithful to the original design. However, these steps could also lead to additional sidewall roughness, although initial results indicate that the propagation losses in curved waveguides remain similar with and without OPC treatment.

Perspectives

New designs are currently being fabricated to take advantage of this advanced platform e.g.: 'non-intuitive' or 'shape optimized' designs [4] and components exploiting the subwavelength regime. This technology can open new paths to improve component performance via insertion loss reduction and increased spectral bandwidth.

RELATED PUBLICATIONS:

- [1] D. Fowler et al., Fiber grating coupler development for Si-photonics process design kits at CEA-LETI, Photonics West conf 2019, DOI: 10.1117/12.2511845
- [2] A. Fay, et al., Mask grade impact on optical transmission losses - EMLC 2019
- [3] C. Dupré et al., Immersion lithography introduction in Si Photonics platform, Photonics West conf 2020
- [4] K. Hassan et al., High-efficiency and broadband photonic polarization rotator based on multilevel shape optimization, Optics Letters 2019, DOI:10.1364/OL.44.001960

Lasing in tensile strained Ge and GeSn microbridge optically pumped cavities

RESEARCH TOPIC:

Germanium, Germanium Tin, Laser, Mid-infrared light emitting, Band structures engineering, Si photonics.

AUTHORS:

V. Reboud, J. Chrétien (IRIG), F.T. Armand Pilon (PSI), L. Casiez, N. Pauc (IRIG), J. Widiez (DCOS), H. Sigg (PSI), J.M. Hartmann (DPFT), V. Calvo (IRIG), A. Chelnokov.

Group-IV elements (such as germanium or germanium-tin) are promising laser materials for silicon based optoelectronics. Germanium, a CMOS-compatible semiconductor, has a favourable band structure which can be tuned by strain or alloying with Sn to become direct.

In the mid-infrared region, we report lasing upon optical pumping:

1. in tensile strained Ge microbridges uniaxially loaded up to 5.9% with a quantum efficiency above 50%,
2. in tensile strained GeSn microbridges with laser emission over a very large wavelength range (from 3.1 up to 4.6 μm at 25 K) and with thresholds lower than $10 \text{ kW}\cdot\text{cm}^{-2}$. Laser operation persists up to 273 K in GeSn laser cavities.

SCIENTIFIC COLLABORATIONS: IRIG, DPFT, DCOS, PAUL SCHEERER INSTITUT

Context and Challenges

The lack of an efficient light source fully compatible with a complementary metal-oxide-semiconductor (CMOS) environment is still the main obstacle to a seamless convergence of electronics and photonics on silicon. Indeed, the indirect nature of the Si bandgap prevents its use as a light emitter. Ge has gained a lot of attention due to its Si CMOS compatibility and its small conduction band-offset between the direct Γ and the indirect L states of only $\approx 140 \text{ meV}$. To close this offset and transform Ge into a direct band gap semiconductor, the application of tensile strain as well as alloying Ge with Sn have become a very active field of research.

Main Results

To have high tensile stress levels in Ge-based epitaxial layers, we make use of stress-enhancement by geometrical patterning as suggested by M. J. Süess *et al.* in Nature Photon. 7, 466-472 (2013). Ge microstructures were fabricated from high-quality optical grade germanium-on-insulator (GeOI) substrates. Tensile strain along $\langle 100 \rangle$ is induced by amplifying the residual strain in GeOI layers using Ge pulling arms on both sides of a central, tiny Ge bridge (thanks to the SiO_2 underetching) (Fig. 1a). Along the same lines, Ge tensor arms can stretch GeSn bridges that were at first epitaxied onto thick Ge strain-relaxed buffers (SRB), themselves on SOI wafers, changing the strain from still compressive in the as-grown state to tensile (Fig. 1b).

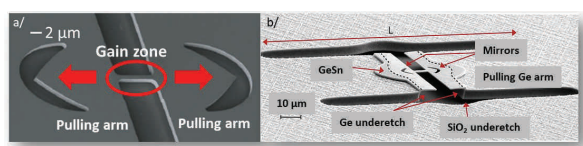


Fig. 1. Scanning electron microscopy (SEM) of strain engineered microbridges with optical lasing cavity: a/ in Ge made from GeOI substrate and b/ in GeSn deposited on a Ge SRB, itself on SOI.

The gain material, either strained Ge or strained GeSn, is embedded in an optical cavity with two parabolically shaped mirrors. For Ge, about 6 % of uniaxial strain is required to close the bandgap offset between Γ and L. Under this configuration, lasing with quantum efficiency above 50 % is observed, but only upon pulsed excitation and up to 100 K (Fig. 2a) [1]. In contrast, for GeSn with 16% of Sn, tensile strain further enhances the system directness. For about 2% of induced tensile strain, the lasing operational limit reaches 273K, i.e. almost room temperature, under pulsed excitation (Fig. 2b) [2].

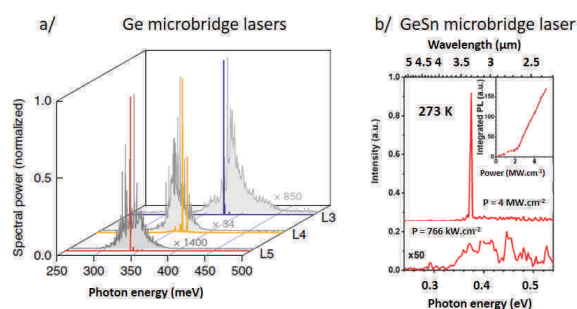


Fig. 2. a/ Normalized spectra taken at 20 K of strained Ge lasers with three length of Ge arms (L3, L4 and L5). In grey: photoluminescence spectra below lasing threshold. b/ Laser spectrum recorded at 273 K of a strained GeSn laser (below and above laser threshold) with its associated light in-light out curve.

Perspectives

Various solutions were evaluated to reach room temperature lasing in Ge-based materials. A combination of strain and Sn alloying was shown to be favourable for optically-pumped RT lasing. Electrical injection in future pin structures would have the advantage, over optical pumping, of enabling a separate control of holes and electron densities and of removing the accumulated carriers continuously or sequentially under reverse-bias. Lasing operation at higher temperatures might be feasible, then.

RELATED PUBLICATIONS:

- [1] F.T. Armand Pilon, A. Lyasota, Y-M Niquet, V. Reboud, V. Calvo, N. Pauc, J. Widiez, C. Bonzon, J.M. Hartmann, A. Chelnokov, J. Faist and H. Sigg, Lasing in strained germanium microbridges, Nature Communications 10(1), 2724 (2019).
- [2] J. Chrétien, N. Pauc, F. A. Pilon, M. Bertrand, Q.-M. Thai, L. Casiez, N. Bernier, H. Dansas, P. Gergaud, E. Delamadeleine, R. Khazaka, H. Sigg, J. Faist, A. Chelnokov, V. Reboud, J.-M. Hartmann, V. Calvo, ACS Photonics, 6, 10, 2462-2469 (2019).

Backside integration of III-V/Si hybrid laser in the Si-SiN photonics platform

RESEARCH TOPIC:

hybrid laser, backside integration, SiN, transceiver, CWDM

AUTHORS:

Q. Wilmart, D. Fowler, K. Hassan, S. Malhouitre, S. Garcia, K. Ribaud, J. Da Fonseca (DPFT), R. Thibon (DPFT), C. Jany (DPFT), S. Olivier

We report on the fabrication and characterization of multilevel Si/SiN/III-V transmitter circuits. Targeting high data rate, the SiN guiding level is monolithically integrated into the LETI's silicon photonics platform to make temperature insensitive multiplexers and broadband fiber couplers. The III-V material is heterogeneously integrated on the backside of the SOI layer in order to make hybrid laser sources. We show single mode operation of a Si/III-V hybrid laser coupled to a SiN waveguide. This result validates the first integration of III-V on the backside of a Si/SiN platform and opens the way towards the versatile integration of hybrid sources on wafers provided by any industrial foundries.

Context and Challenges

The constantly growing network traffic in data centers requires low cost, high speed and energy efficient transmission solutions. Integrating SiN, a low thermal coefficient material, in a photonics platform allows the realization of wavelength multiplexers with low temperature sensitivity, reducing the power consumption of the thermo-electric controllers placed at the packaging level. A Si/SiN platform is therefore an attractive solution to make energy efficient high data rate optical transceivers. On the other hand, integrating III-V material on Si for hybrid laser sources and electro absorption modulators reduces packaging complexity and improves the scalability to a larger number of channels. However, the co-integration of Si, SiN, and III-V is challenging, as it requires some part of the fabrication to be done on the wafer backside.

Main Results

The design of hybrid laser cavities dictates that Si and III-V are less than 150nm apart for efficient optical coupling. Therefore, Si (from 300nm-thick SOI) and SiN (deposited by Plasma Enhanced Chemical Vapor deposition) are first patterned on the wafer frontside. Then a carrier substrate is bonded, wafers are flipped and the original substrate is removed. The process is resumed on the backside with an amorphous silicon thickening step (500nm-thick Si is necessary for a good III-V/Si effective index matching). The associated patterning step includes feature sizes down to 120nm thus requiring the use of 193-nm UV photolithography with frontside-backside alignment. Notably, the SiN and the amorphous silicon are deposited at low temperature (<350°C) making the process compatible with the presence of a backend of line. The multi-quantum well III-V substrate is bonded on the back of Si and patterned. A total of 12 backside patterning levels is necessary to complete the fabrication (final cross section in Fig 1 a and SEM image in Fig. 1 b).

The Si/SiN platform includes a Coarse Wavelength Division Multiplexing (CWDM) SiN multiplexer based on Echelle gratings [1] and a SiN/Si hybrid grating fiber coupler specially designed for backside coupling and featuring a 50nm (-1dB) bandwidth

(Fig 1. c). We show the operation of a Distributed FeedBack (DFB) laser (Fig. 1 d). The laser shows a single mode at 1312nm with a side mode suppression ratio of 44dB and an estimated output power (in the waveguides) of 0.8mW. Notably, the hybrid DFB laser is coupled to a SiN waveguide and the chip output is performed through the backside SiN/Si grating fiber coupler [2]. This demonstration is the first realization of a III-V/Si hybrid laser on the backside of an Si/SiN platform.

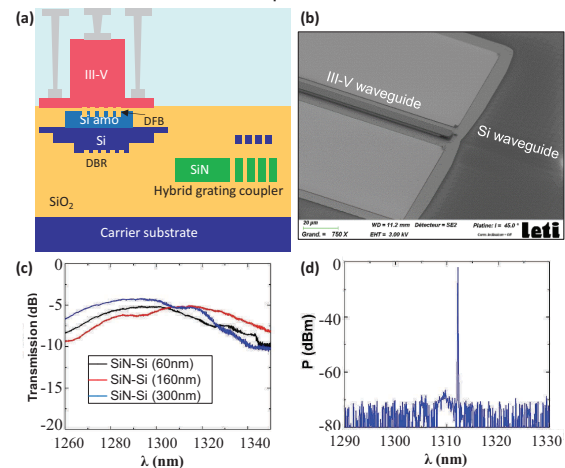


Fig. 1. (a) Si/SiN/III-V integration. (b) SEM image of III-V waveguide. (c) SiN/Si hybrid grating coupler spectrum. Black, red and blue lines correspond to 60, 160 and 300nm Si thickness respectively. (d) Si/III-V DFB laser spectrum.

Perspectives

The fabrication of III-V structures on the backside is a promising integration path for wafers coming from industrial foundries with a stabilized process flow: the III-V integration can be done on the backside of 300mm wafers, without any stack modification while remaining CMOS compatible.

RELATED PUBLICATIONS:

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- [2] Public summary of the H2020 european project COSMICC (www.h2020-cosmicc.com)

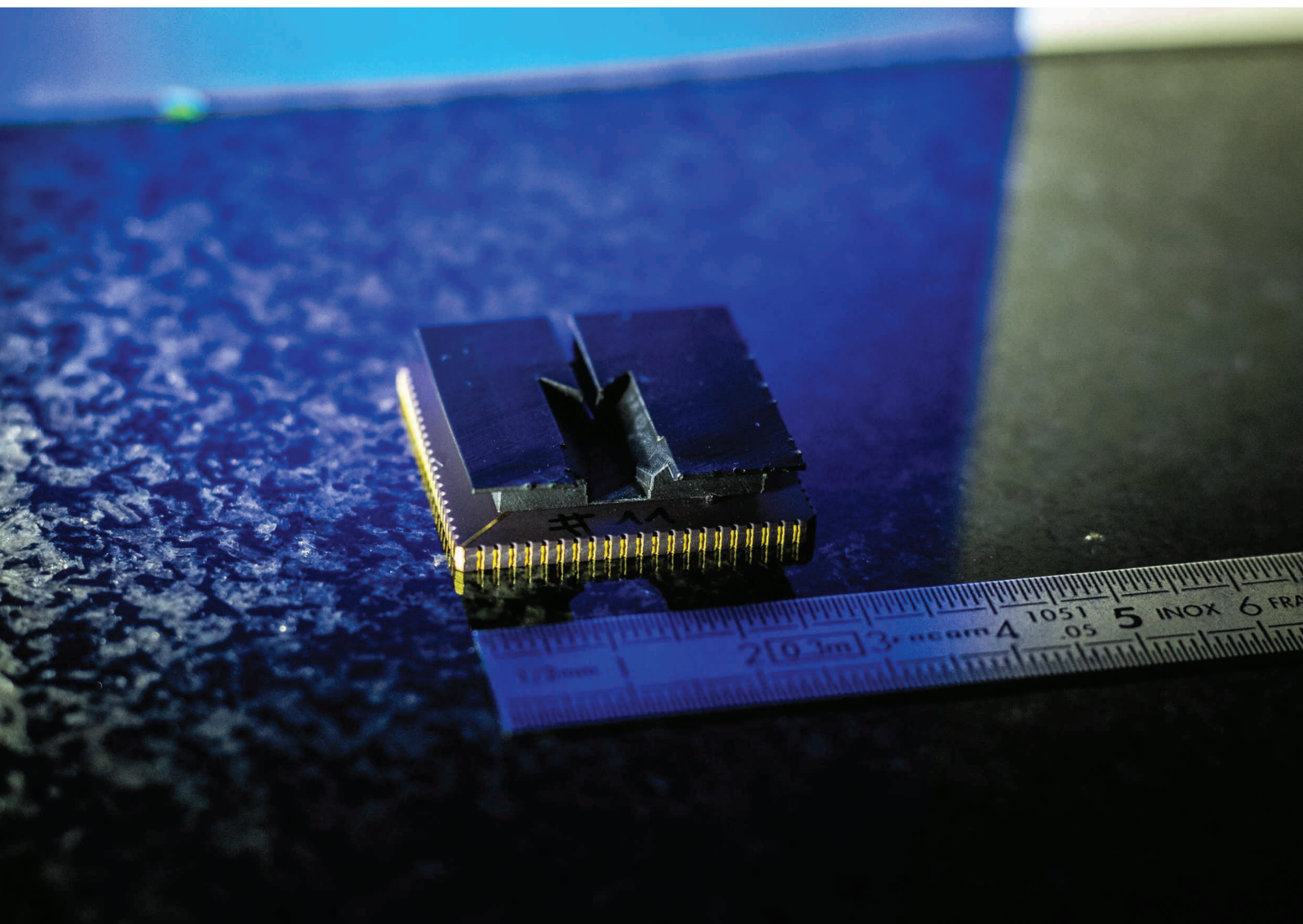


Photo G. Jobert ©CEA-Leti

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OPTICAL ENVIRONMENTAL SENSORS

- **Si-integrated photonic “nose” smells volatile organic compounds**
- **Mid-IR lens-less imagers identify microbes**
- **Extreme downsizing of Si-integrated photoacoustic trace gas analyzers**
- **Compact sensor of aerosol particles uses imagery of optical scattering**

Silicon-photonics-integrated olfactory sensors

RESEARCH TOPIC:

Silicon photonic biosensors and odor sensors

AUTHORS:

L. Laplatine, M. Fournier, M. Dupoy, J. Gorry, R. Mathey (IRIG), A. Buhot (IRIG), Y. Hou-BROUTIN (IRIG), G. Rolland (Aryballe), C. Herrier (Aryballe), J. Liu (Aryballe), T. Livache (Aryballe).

The ability to mimic human senses using devices such as cameras or microphones has a major impact on society, from telecommunication, creative content or digital memories thanks to audio-visual recordings. Yet, recording and analyzing smells remains a critical challenge. Affordable and reliable odor sensors would be a great asset in diverse areas such as air quality monitoring, quality control for the food and perfume industries, well-being for people suffering from anosmia or even personal health. Here, we present a new olfactory sensor based on arrays of silicon photonic interferometers. By surface functionalization with biomolecules, we are able to identify Volatile Organic Compounds (VOC). Optoelectronic and fluidic integration allows miniaturizing the system down to portable devices.

SCIENTIFIC COLLABORATIONS: Aryballe Technologies, DRF/IRIG/SYMMES/CREAB, funded by the Nanoscience Foundation, Grenoble

Context and Challenges

Olfaction implies the detection and differentiation of thousands of different VOC. As in human olfaction, electronic noses rely on a limited number of non-specific sensors with different physicochemical properties. The global response of the sensor array, called a signature, correlates to a specific smell. Odor identification then consists in searching for similar signatures in a database. Although electronic noses based on metal oxide semiconductors have been investigated since the 80's, they never managed to reach the consumer market. Nowadays, silicon photonics could tackle this challenge by offering low-cost mass production of highly sensitive and compact odor sensors. In 2018, CEA Grenoble and Aryballe Technologies started a collaboration funded by the Nanoscience Foundation, Grenoble, to demonstrate the feasibility of such photonic olfactory sensors.

Main Results

We have developed a silicon photonic platform optimized for odor and biological sensing. The platform includes fiber grating couplers, low-loss routing and sensing waveguides, microring resonators with quality factors up to 45 000, 120° hybrid MMI combiners as well as coherent Mach-Zehnder Interferometers (MZI) with spiral waveguides specifically designed to reduce spectral noise in phase readout. Their bulk limit of detection was measured in the 10^{-7} RIU range. By surface functionalization (IRIG/SYMMES), the MZI sensing waveguides were arrayed with peptides at Aryballe (Fig. 1). Upon injection of VOC in air, the phase shift induced by the refractive index change can be recovered from the intensity measurement of the three optical outputs of each MZI by an imager (Fig.2). The maximum signal reached by each MZI leads to a signature that is specific to a given smell (Fig.3). A USB powered prototype was presented at CES 2020 in Las Vegas by Aryballe Technologies [1].

Perspectives

A third wafer lot is being fabricated at Leti's 200mm pilot line. The dies with optimized components and reduced footprint will integrate arrays of 64 MZI to improve identification capabilities.

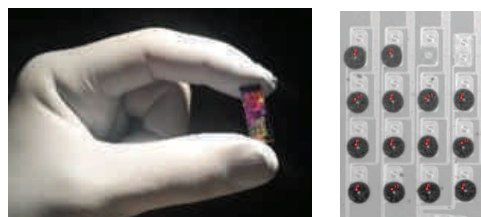


Fig.1. Left: photonic die. Right: surface functionalization of 500-μm-pitch MZI by microdroplets containing biomolecules.

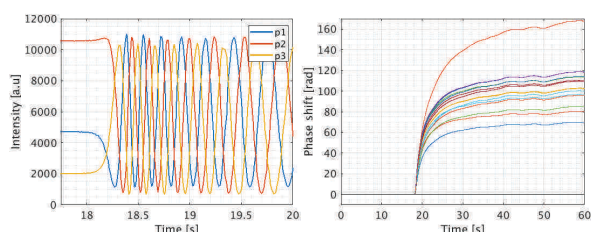


Fig.2. Left: coherent intensity variations for one MZI. Right: Sensorgram of pure butanol in air (3-σ noise of ~17 mrad)

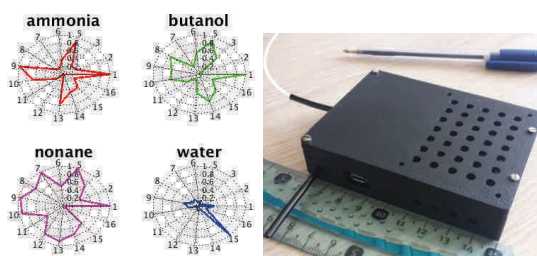


Fig.3. Left: VOC signatures. Right: Leti's prototype integrating a laser, an imager, a PCB driver, a pump and fluidic tubing.

RELATED PUBLICATIONS:

[1] <https://aryballe.com/aryballe-announces-new-high-volume-low-cost-universal-odor-sensor-for-consumer-applications/>

Mid-infrared multispectral lensless imaging for wide-field and label-free microbial identification

RESEARCH TOPIC:

Microbial diagnosis, multispectral imaging, lensless Imaging, infrared spectrometry

AUTHORS:

Joël Le Galudec, Mathieu Dupoy, Véronique Rebuffel, Pierre Marcoux

Microbial diagnosis is a critical process aiming at identifying the species contained in a biological sample. Here is presented an innovative method for label-free optical identification of microorganisms, based on the multispectral infrared imaging of colonies. This lensless imaging technique enables a high-throughput analysis and wide-field analysis of agar plates. It relies on acquisition of an optical fingerprint, gathering both morphological and biochemical features on a single multispectral image, which will allow obtaining very high correct identification rates.

A first database containing more than 1000 multispectral images of colonies belonging to five different species has already been acquired with this system, resulting in a correct identification rate above 92%. These very first results are promising and could be considerably improved by optimizing the image descriptors currently used and implementing the ongoing development of uncooled bolometer technology.

Context and Challenges

Identification of microorganisms such as bacteria, yeasts or fungi, has critical implications for the industry, national security and of course healthcare. This process strongly relies on microorganisms culture, which is most of the time done by spreading on a solid culture medium, poured inside a Petri dish. Several technologies have already been developed to bypass this culture step, but the Petri dish is still a simple, cheap and powerful tool for microbiological diagnosis.

However, a fully automated instrument allowing direct microbial identification from Petri dish observation, without reagent nor further sample preparation, has not yet been created. Such technology would allow to quickly performing hundreds of tests to find potentially pathogenic microorganisms and, if necessary, could be used to guide the choice of further analysis.

Here are presented the first results regarding a new wide field and label-free identification technology which could be applied to Petri dish analysis: mid-infrared multispectral lensless imaging.

Main Results

This technology is based on images acquisition of an object at a few infrared wavelength, which resonate with biologically relevant chemical bounds (Fig.1). For this proof of concept, the objective was to obtain a first multispectral images database and evaluate the system capability to distinguish between a few microbial species, with the help of machine learning classification.

For this objective, a simple transmission setup consisting of a Quantum Cascade Lasers light source and an imager, a square 2.72 by 2.72 mm uncooled bolometer array, was implemented. More 1000 microbial colonies belonging to five different species have been recorded and analyzed. Data analysis was fully automated and relied on a Support Vector Machine (SVM) to classify colonies based on several morphological and spectral parameters (colony radius, roundness, transmittance at each

wavelength, skewness, donutness and grey comatrix difference). Classification efficiency was evaluated via a tenfold cross-validation test.

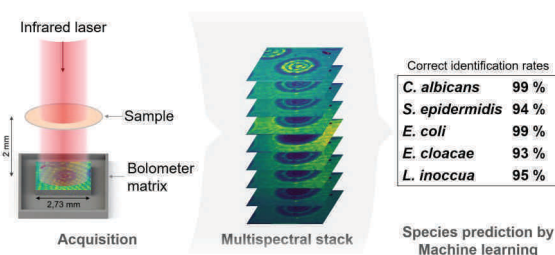


Fig. 1 On the left, measurement setup, in the middle, series of 10 images on a colony, on the right, classification results after machine learning.

The SVM classification yield significant results, with a correct identification ratio for the five species comprised between 92% and 99%. Two closely related species (*Escherichia coli* and *Enterobacter cloacae*) are correctly distinguished one from another, with a confusion rate around 1%.

Perspectives

This first experiment has shown that this system is as effective as other optical techniques to identify bacteria. However, data analysis could be dramatically improved with work on the classification method and the image descriptor. For some species, only 150 colonies were imaged, which also impaired the quality of the results.

The next experiments will focus on the acquisition of a new database containing some extremely closely related species, which will help to push the boundaries of the method. Further work is still planned on the data analysis part. In the end, multispectral lensless imaging has been proved as a promising technique for microbial identification and could be used as a routine water quality assessment technology.

RELATED PUBLICATIONS:

[1] J. Le Galudec, M. Dupoy, V. Rebuffel, et P. R. Marcoux, « Mid-infrared multispectral lensless imaging for wide-field and label-free microbial identification », in Biomedical Spectroscopy, Microscopy, and Imaging, avr. 2020, vol. 11359, p. 113590B, doi: 10.1117/12.2557502.

Downsizing and integration on silicon for photoacoustic detection of trace gas

RESEARCH TOPIC:

Photoacoustics, trace gas detection, miniaturization

AUTHORS:

A. Glière, J.-G. Coutard, T. Verdot (DCOS) and S. Nicoletti

Downsizing and compatibility with MEMS silicon foundries is an attractive path towards a large diffusion of photoacoustic trace gas sensors. Three generations of miniaturised components have been designed at CEA-LETI, using complementary analytical or numerical models, as well as numerical optimisation techniques. The devices have then been produced, either by additive manufacturing or by silicon micro-fabrication techniques in our facilities, and finally characterised. All three versions demonstrated sub-ppm limit of detection. Each one has specific benefits and drawbacks regarding fabrication, implementation and ease of use, and thus its own conditions of use.

SCIENTIFIC COLLABORATIONS:

Context and Challenges

Integration on silicon platform led in the recent years to major successes in the domain of micro-electromechanical systems. The transposition of this strategy to photoacoustic (PA) based trace gas sensors has been the object of a continuous effort since almost ten years in our laboratory [1], aiming at a widespread usage, for instance, in indoor and outdoor air quality measurement or industrial process control.

It is noticeable that, as the photoacoustic signal is inversely proportional to the chamber volume, reducing the size of the sensor is a way to simultaneously improve production cost, mass deployment potential and measurement sensitivity.

Main Results

The timeline of our PA cells downsizing approach has been marked by the design, fabrication and characterization of three generations of miniature photoacoustic components (Fig. 1), namely a 40 mm³ 3D-printed metal cell [2], a 3.7 mm³ micro-fabricated silicon cell [3] and a 2.3 mm³ silicon cell embedding its own piezo resistive pressure sensor [4].

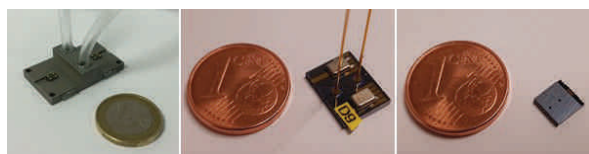


Fig. 1. Three generations of miniaturized PA cells. From left to right, the 3D-printed metal cell, the micro-fabricated silicon cell and the silicon cell with its built-in piezoresistive pressure sensor.

In order to secure the design process, a range of analytical, lumped-element or numerical models has been developed in order to address the multiphysics (optical, acoustical and mechanical) issues. Some of the components have been designed with the help of metamodel-based numerical optimisation [5].

The devices characterisation demonstrate that all three generations of PA sensors achieve sub-ppm limit of detection [1] (see for instance Fig. 2). However, each has its own benefits and drawbacks, regarding fabrication, implementation and ease of use. For instance, the 3D-printed cell is well adapted for rapid prototyping and benchtop testing, whereas the micro-fabricated silicon cell would be better fit for industrial series involving pick-and-place soldering of the MEMS microphones and advanced packaging. The third generation component is far more demanding in terms of technological means requirements but it would ultimately be produced at high-volume and at a negligible cost.

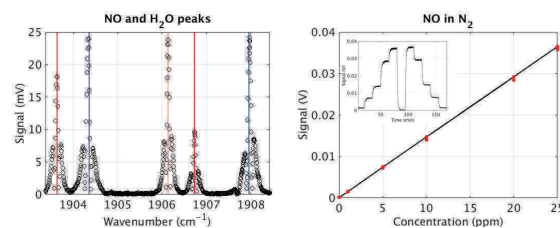


Fig. 2. Measurements of NO with the micro-fabricated silicon cell. Left figure: measured spectrum (o), overlaid with the spectral lines of NO (red) and ambient water vapour (blue). Right figure: linear fit of the signal versus concentration, with concentration range shown in inset.

Perspectives

In parallel to this work on PA cells, significant progress has also been made recently in our institute towards the wafer scale fabrication of quantum cascade lasers and mid-infrared photonic integrated circuits. It thus appears that the goal stated at the beginning of this research, namely to build a PA sensor combining, on the same chip, a mid-infrared laser, a light injection circuit and a PA cell including an integrated pressure sensor is now within reach.

RELATED PUBLICATIONS:

- [1] A. Glière et al., "Downsizing and Silicon Integration of Photoacoustic Gas Cells," *Int. J. Thermophys.*, vol. 41, no. 2, 2020.
- [2] J. Rouxel et al., "Miniaturized differential Helmholtz resonators for photoacoustic trace gas detection," *Sens. Actuators B: Chem.*, vol. 236, 2016.
- [3] J.-G. Coutard et al., "Photoacoustic cell on silicon for mid-infrared QCL-based spectroscopic analysis," in *MOEMS and Miniaturized Systems XVIII*, San Francisco, USA, Feb. 02-07, 2019, vol. 10931.
- [4] H. Lhermet et al., "Micro-photoacoustic cell with integrated microphone for sub-ppm gas sensing," in *Transducers 2019*, Berlin, Germany, Jun. 23-27, 2019.
- [5] C. Durantin et al. "Multifidelity surrogate modeling based on radial basis functions," *Struct. Multidisc. Optim.*, vol. 56, no. 5, 2017.

Miniature particulate matter counter and analyzer based on lens-free imaging of light scattering signatures with a holed image sensor

RESEARCH TOPIC:

Air Quality, Particulate matter sensor, light scattering, CMOS image sensor

AUTHORS:

G. Jobert, P. Barritault, S. Boutami, S. Nicoletti, J. Michelot (Pyxalis), P. Monsinjon (Pyxalis), P. Lienhard (Pyxalis), M. Fournier

We propose a Particulate Matters (PM) sensor based on the imagery of scattering signature by single particles. This optical sensor combines a visible fibered light source and a vertical air channel drilled out of a holed retina. The signatures measured for polystyrene spheres demonstrate the possibility of single particle measurement, for diameters ranging from 300 nm to 4 μm , as well as a strong variation of the signatures with the particle diameter, as predicted by Mie's theory. This new generation of PM sensor is quantitatively sensitive to the nature, size and number of PM in the air. It thus offers new possibilities for Air Quality monitoring.

SCIENTIFIC COLLABORATIONS: Pyxalis

Context and Challenges

Today, quantitative measurement of Particulate Matters (PM) is a major concern in air quality monitoring. Low cost and portable systems exist. They are based on the measurement, by a single photodiode, of light scattering (LED) by PM. However, due to their simplicity, these systems only offer a weak information which can be summarized to basic counting. This is the challenge we propose to address: creating a new generation of PM sensor having the ability to determine the nature, size and number of PM in air. Compactness, low cost and low power consumption, associated with data analysis software will enable a dense spatial mapping at the city scale.

Main Results

To enrich the information recorded by our light diffusion based-sensor, we have replaced the single photodiode by a matrix of photodiodes: a CMOS imager. As can be seen in Fig. 1, the imager is drilled; the particles to be detected pass through this hole, the fluidic channel, and are flashed by the light coming from an optical fiber.

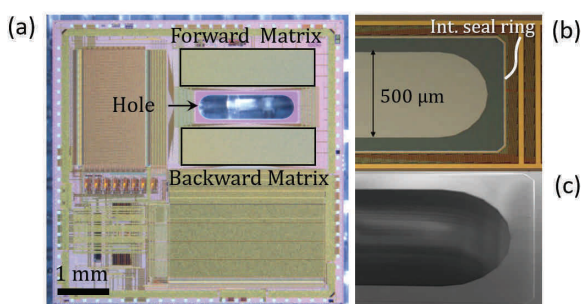


Fig.1 imager (two sub-matrices) and central hole.

The detection occurs very close (1.5 mm) to the imager thus enabling single particle detection with a high Signal-to-Noise

ratio. The system presented in Fig. 2, also includes a cloaker which protects the imager from stray light; the heart of the system is compact and fits in a few cm^3 .

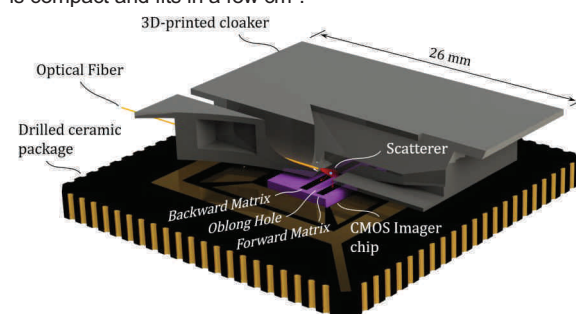


Fig.2 PM Detection system (imager, optical source and cloaker)

The imager records the angular scattering signature of each particle. Fig. 3 shows a high dependence of these signatures with particles' size for Polystyrene Sphere. A good correlation between experiment and simulation is also demonstrated.

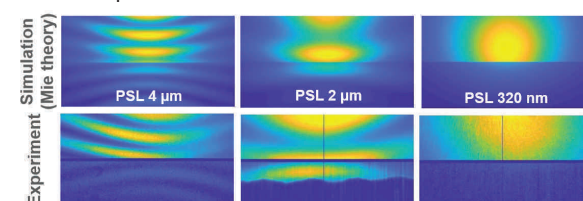


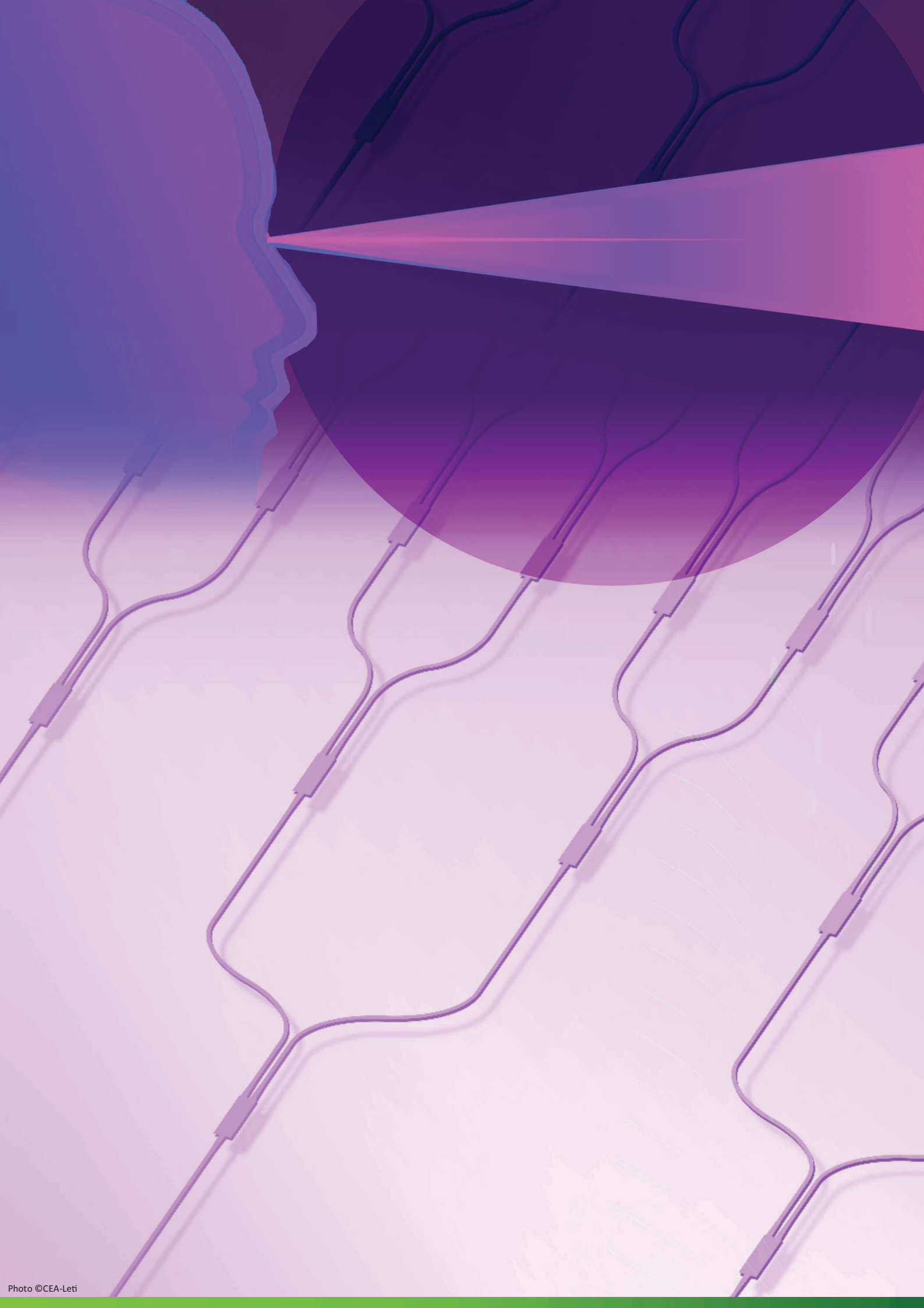
Fig.3 Experiment vs. simulation for Polystyrene spheres

Perspectives

This first proof of concept will be followed by measurements on more realistic PM: dust, soot, metallic or organic particles... The database collected will be the input for a machine learning algorithm, the final goal being predictive measurement.

RELATED PUBLICATIONS:

[1] Miniature particulate matter counter and analyzer based on lens-free imaging of light scattering signatures with a holed image sensor, Jobert *et al.*, Sensors and Actuators Reports, 2, 1, 2020, <https://doi.org/10.1016/j.snrs.2020.100010>



07

SOLID STATE LIGHTING AND DISPLAYS

- **OLED μ -displays packaged with UV-curable thin-film hard coat**
- **Curved OLED μ -displays**
- **Size of GaN μ -LEDs impacts their efficiency**
- **GaN μ -LEDs passivated with ALD Al_2O_3**
- **High brightness full color GaN μ -displays**
- **Macro displays based on GaN μ -LEDs**
- **Direct retinal projection displays: design and integration**

UV-curable thin-film packaging for OLED-based microdisplays

RESEARCH TOPIC:

Organic electronics; OLED; Thin-film encapsulation; Sol-gel; Hybrid coatings; atomic layer deposition (ALD)

AUTHORS:

M. Provost, A. Suhm, V. Gaud (Polyrise SAS), K. Raulin (Polyrise SAS), V. Mandrillon and T. Maindron

A thin-film Hard-Coat (HC) layer, made from a silica-based hybrid polymer synthesized by sol-gel process, was investigated for the encapsulation and mechanical packaging of top-emission OLED (Organic Light-Emitting Diodes) used in microdisplays as an alternative solution to individual glass-lid protection. The HC is deposited by spin-coating onto the wafer containing OLED dies and the HC pattern is fabricated by a standard photolithography process. OLED samples are then characterized following different ageing tests (lifetime at constant current drive and storage in 60°C, 90% RH). It will be shown that the new HC material can reach the barrier performance of a reference glass-lid encapsulation.

SCIENTIFIC COLLABORATIONS: Polyrise SAS (Bordeaux) and MicroOLED SAS (Grenoble)

Context and Challenges

It is widely known that OLEDs are highly sensitive to moisture and oxygen ingress and require high barrier encapsulation [1]. Moreover, a specific protection needs to be added to protect the device from mechanical ingress. Depending on the application, various options from glass lids to flexible barriers have been developed. However, the former offers high mechanical protection but suffers from long implementation processes, while the latter typically exhibit low hardness and poor wear resistance. This work aims to develop an alternative collective packaging solution using a thin-film HC layer directly processed onto OLED circuits by photolithography. The mechanical and optical properties of the HC layer and the reliability of the OLEDs with this new packaging (Al_2O_3 by ALD + HC) are investigated. Detailed results can be found in [2].

Main Results

Mechanical characterization. The polymer matrix provides various advantages in term of flexibility, toughness and processability but exhibit low hardness and abrasion resistance. On the other hand, fillers such as the silica nanoparticles used in this study mainly improve the mechanical strength of the coating but can induce cracks and reduced transparency during film drying. Enhancement of both advantages of polymer matrix and silica part in the HC can be obtained by optimizing the balance between organic and inorganic and by controlling the structure of the hybrid polymer composite. The abrasion resistance and adhesion of the HC are notably improved compared to a reference PMMA layer and the film hardness is also enhanced.

Table 1. Mechanical properties of the HC compared to a pure polymer (PMMA) and a pure SiO_2 film (sputtering deposition).

	PMMA 4-40 μm	Hybrid HC 3,5 μm	SiO_2 1 μm
Hardness (GPa)	0,13 [7]	0,19	0,34
Young Modulus (GPa)	2,75 [7]	4,5	6
Abrasion ISO9211-0104	19 %	6 %	0 %
Adhesion on Al_2O_3	low	medium	high

The wear resistance of the HC appears to be sufficient for the dicing, cleaning and also the handling of OLED dies. On the other hand, the HC shows improved flexibility and resilience

compared to an inorganic SiO_2 layer, leading to a less brittle coating.

OLED ageing test (at constant current drive, laboratory ambient conditions). No electric failure can be observed on aged samples, neither any dark spot. The OLED sample with the HC packaging and a single Al_2O_3 barrier film, Fig. 1) exhibits systematically same luminance decay as for reference OLEDs (with glass lid). In conclusion, the HC processing does not induce any degradation of the OLED stack.

Evaluation of HC barrier properties (storage of devices in 60°C/90% RH conditions). Accelerated aging tests were performed on OLED with the HC layer, Fig. 1. No swelling or delamination of the HC film can be observed due to thermal choc or moisture ingress over 300 hours of ageing test. The HC layer not only provides interesting mechanical properties, but also display good barrier protection combined to the single barrier layer (Al_2O_3), deposited by ALD.

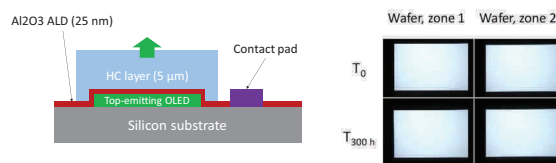


Fig. 1. (left) OLED architecture with HC on top of a single Al_2O_3 barrier layer (ALD); (right) picture of OLED samples (white emission) before and after (+ 300 h) the storage test (@60°C, 90%RH)

Perspectives

The OLED (micro)display technology require an improved reliability in terms of encapsulation. Thin-film alternatives to the glass lid are developed and promote environmental as well as mechanical resistance. These packaging scenarios also opens up the possibilities for the use of flexible or conformable substrate to achieve curved and flexible displays that cannot be encapsulated with rigid glass lids [3].

RELATED PUBLICATIONS:

- [1] Maindron, T., et al. (2016). "Defect analysis in low temperature atomic layer deposited Al_2O_3 and physical vapor deposited SiO_2 barrier films and combination of both to achieve high quality moisture barriers." Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films. DOI:10.1116/1.4947289
- [2] Provost, M., et al. (2018). "Influence of silane coupling agent on the properties of UV curable SiO_2 -PMMA hybrid nanocomposite." Journal of Sol-Gel Science and Technology. DOI:10.1007/s10971-018-4861-1
- [3] Maindron, T. et al. (2019). "Curved OLED microdisplays". J. Soc. Inf. Display. DOI:10.1002/jsid.824

Curved OLED microdisplays

RESEARCH TOPIC:

Microdisplays, Hardcoat protection layer, Curving process, Augmented Reality (AR), Virtual Reality (VR)

AUTHORS:

Tony Maindron, Bertrand Chambion, Marion Provost, Aurélie Vandeneynde, Patrick Peray (Marc Zussy, Jérôme Dechamp, Cyrille Rossat, Stéphanie Gonnin)

Technical background for CMOS substrate thinning of CEA-LETI has been applied to realize curved OLED-based microdisplays. It will be shown that test OLEDs made onto silicon wafers as well as 873 × 500 WVGA, 0.38" diagonal, and an innovative 1920 × 1200 WUXGA, 1" diagonal, CMOS based microdisplays can be curved at R=45mm radius of curvature (cylindrical shape/1D) with no negative impact onto the circuit electrical characteristics [1]. This feature can allow significant innovation on the system and application because it can help to redesign simpler and lighter optical engine systems, in the same manner as for curved image sensors. These results can be obtained owing to the integration of a new protective hardcoat layer that has been used in conjunction with a robust thin-film encapsulation to protect OLEDs from mechanical stress (from process steps and handling) and air ingress (oxidizing gas of the atmosphere) respectively.

SCIENTIFIC COLLABORATIONS : MICROOLED

Context and Challenges

Microdisplays are used in head mounted displays (HMD) for applications such virtual reality (VR) or augmented reality (AR). A main feature of microdisplays is that they are typically fabricated as flat image-generating surfaces. Therefore, they generate a rectilinear flat image that must be transformed into a curved image wave-front representation for projection into the eye. Flat image sources force the design and use of complex eyepiece optics that efficiently collect and convert the flat image into a curved field-of-view (FOV) of optical flux relayed to the eye. Unfortunately, large footprint, high weight, and expense of display optics often prevent the integration of microdisplays into applications where weight and space are critical parameters. The CEA-LETI institute has quite a long story developing curved image sensors [2-3] that can address all the issues mentioned above. This knowhow has been used in order to develop curved microdisplays.

Main Results

We have first assessed the issue related to the development of a suitable thin (~ few μm) flexible hardcoat (HC) OLED protection layer deposited on top of a suitable thin-film encapsulation (TFE) (see Fig.1).

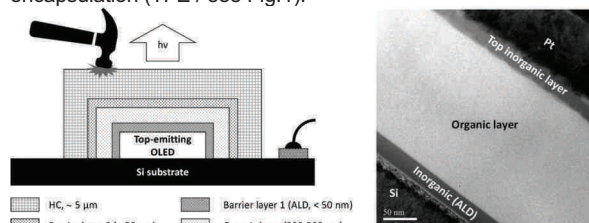


Fig. 1. (Left) Schematic of the OLED top-emitting architecture [Si/OLED] used in this work; (right) TEM cross-section imaging of the TFE showing the [inorganic/organic/inorganic] basic architecture.

The whole thickness of TFE does not exceed 300 nm, while at the same time it guarantees a very high edge sealing of the

individual OLED. The main innovation in this work lies in the thin-film processing of an additional protective HC layer, as thin as 4 to 5 μm , made of a dedicated flexible sol-gel hybrid nanocomposite deposited from solution directly onto the TFE of the OLED [4]. The chemical composition of HCs as well as process steps (annealing temperature, solvents) appeared to be fully compatible with the TFE and OLED underneath. No degradation of the TFE has been observed, and no defect such as dark spots or electrical failures have been observed on the OLED after the HC completion.

Then, we have applied a thinning and bending processes to OLED testing samples (without CMOS underneath) and fully functional microdisplay (see Fig. 2).

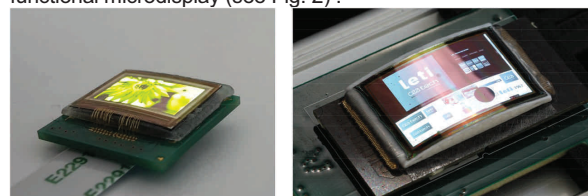


Fig. 2. (Left) 873 × 500 WVGA monochrome yellow, 0.38" diagonal microdisplay and (right) 1920 × 1200 WUXGA monochrome white, 1" diagonal microdisplay, both curved at Rc = 45 mm.

We showed that a dedicated process for 1D cylindrical curving of single OLED chips can be achieved, if one takes care of the fragile OLED surface during the mechanical grinding process. In the end, we showed that it is possible to curve at Rc = 45 mm a 873 × 500 WVGA, 0.38" diagonal microdisplay as well as a larger 1920 × 1200 WUXGA, 1" diagonal, microdisplay (Fig. 2).

Perspective

Future work and perspectives include the test of 2D curving features of microdisplays as well as reliability studies of curved OLED samples. Packaging scenarios are also under development to provide a reliable system compatible with mass production. Interfacing the curved display system with a suitable optical engine is also mandatory.

RELATED PUBLICATIONS:

- [1] Maindron, T., Chambion, B., Provost, M., et al. Curved OLED microdisplays. *J Soc Inf Display*. 2019; 27: 723– 733.
- [2] Chambion B, Nikitushkina L, Gaeremynck Y, et al. Tunable curvature of large visible CMOS image sensors: towards new optical functions and system miniaturization. 2016 IEEE 66th Electronic Components and Technology Conference (ECTC). 2016.
- [3] Chambion B, Gaschet C, Behaghel T, et al. Curved sensors for compact high-resolution wide-field designs: prototype demonstration and optical characterization. 2016 SPIE proceedings 10539, Photonic Instrumentation Engineering V: 1053913. 2018.
- [4] Provost M, Raulin K, Maindron T, Gaud V. Influence of silane coupling agent on the properties of UV curable SiO₂-PMMA hybrid nanocomposite. *Journal of Sol-Gel Science and Technology*. 2018;89:796–806. <https://doi.org/10.1007/s10971-018-4861-1>

InGaN/GaN μ LED spice DC-modeling with size-dependent ABC quantum efficiency model integration

RESEARCH TOPIC:

InGaN/GaN, μ LED, SPICE simulations, ABC model, quantum efficiency

AUTHORS:

Anis Daami and François Olivier

We present the use of a SPICE modelling technique to describe and simulate the electro-optical behavior of the μ LED. A sub-circuit portrayal of the whole device is used to describe current-voltage behavior and the optical power performance of the device based on the ABC model. We suggest an innovative method to derive instantaneously the carrier concentration from the simulated electrical current in order to determine the μ LED quantum efficiency. In a second step, we have add a statistical approach into the SPICE model in order to apprehend the spread of experimental data. This μ LED SPICE modelling approach is very important to allow the design of robust pixel driving circuits.

SCIENTIFIC COLLABORATIONS: III-V Lab

Context and Challenges

μ LED based arrays are becoming a major keystone in the VR, AR technology world. Indeed many companies are awaiting robust μ -displays to integrate them in their products. Therefore, a full and detailed description of the electro-optical behavior of μ LEDs has become necessary to allow robust designs of CMOS driving circuits for these displays [1].

Main Results

Figure 1(a) shows the equivalent electrical circuit used to model the electrical behavior of the LED. It consists of a SPICE LEVEL 1 ideal diode (D), a series resistor (RS) and a parallel resistor (RP). This sub-circuit has two input pins representing the LED anode and cathode. The light output behavior is described by a virtual current-controlled current source (F) which is transparent to the final user.

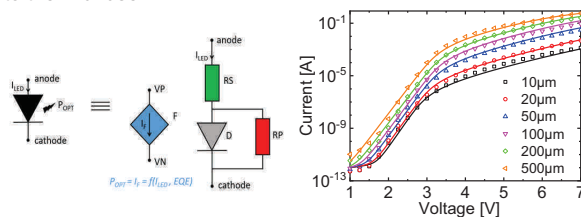


Fig. 1. (a) Equivalent electrical model sub-circuit and (b) adjusted current-voltage simulations versus measurements

Based on the new ABC model description [2,3] of the current density $J_{LED} = q \cdot t \cdot \left(A \cdot \frac{p}{s} \cdot n + B \cdot n^2 + C \cdot n^3 \right)$, a 3rd degree polynomial resolution is implemented in the model itself for each current-voltage point to determine the carrier density n . This allows the calculus of the external quantum efficiency EQE of the μ LED as $EQE = LEE \cdot \frac{B \cdot n^2}{A \cdot \frac{p}{s} \cdot n + B \cdot n^2 + C \cdot n^3}$ where LEE is the light extraction efficiency. We show on figure 2 the simulation results and experimental

data of the EQE versus current density for different μ LED sizes. It is evident that our implemented solution is functional and precisely describes the EQE size behavior of InGaN/GaN μ LEDs.

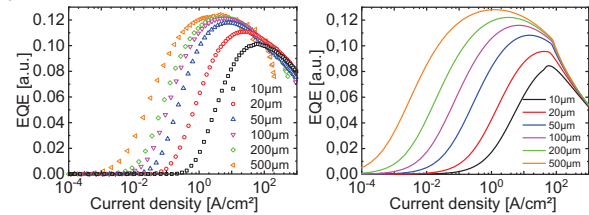


Fig. 2 External quantum efficiency versus current density (a) experimental data (b) SPICE simulations

Finally, we have added a statistical description on the ABC model parameters in order to take into account technological spread. This allows designers through Monte Carlo simulations in order to mimic realistic μ -displays (see figure 3).

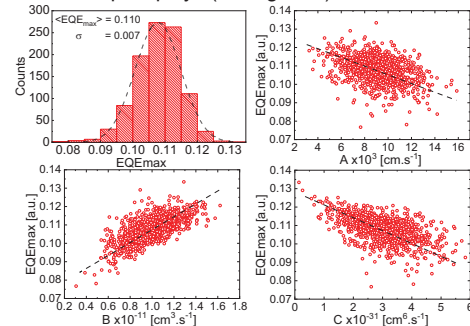


Fig. 3. 1000 run Monte Carlo SPICE simulation results for a 50 μ m LED: validation of the implemented statistical model

Perspectives

In order to be more precise, this SPICE model library has to integrate the AC behavior of μ LEDs.

RELATED PUBLICATIONS:

- [1] Daami, A., Olivier, F., "InGaN/GaN μ LED SPICE modelling with size dependent ABC model integration", Proc. SPIE 10912, Physics and Simulation of Optoelectronic Devices XXVII, 109120E (26 February 2019)
- [2] Daami, A., Olivier, F., Dupré, L., Henry, F., Templier, F., "Electro-optical size-dependence investigation in GaN micro-LED devices", SID Int. Symp. Digest Tech. Papers, 49(1), 790-793 (2018).
- [3] Olivier, F., Daami, A., Licitra, C., Templier, F., "Shockley-Read-Hall and Auger non-radiative recombination in GaN based LEDs: A size effect study", Appl. Phys. Lett., 111, 022104, (2017).

Analysis of InGaN surfaces after chemical treatments and atomic layer deposition of Al_2O_3 for μLED applications¹

RESEARCH TOPIC:

μLED , InGaN passivation, XPS-WDXRF, Al_2O_3 -ALD, surface treatments

AUTHORS:

Corentin Le Maoult, David Vaufrey, François Martin*, Eugénie Martinez*, Emmanuel Nolot*, Stéphane Cadot* (*LETI/DPFT) Etienne Gheeraert* (*Institut Néel)

This article deals with μLED passivation and focus on InGaN, which is the most sensitive material to surface SRH non-radiative recombination in the LED stack. It highlighted the significance of the chemical pre-treatment or cleaning step before the deposition of a passivating dielectric such as Al_2O_3 by ALD. Based on XPS and WDXRF measurements, HCl or $(\text{NH}_4)_2\text{S}$ seems to selectively etch indium whereas NH_4OH is helpful to promote the nucleation of an alumina layer during the first few ALD cycles. Low oxidizing Al_2O_3 deposition process, such as ALD in comparison to PEALD, limits oxidation of indium. Efforts are also focused on Al_2O_3 growth kinetics thanks to WDXRF measurements since it allows to evaluate quantitatively the grafting of aluminum after various surface exposure treatments.

SCIENTIFIC COLLABORATIONS: Univ. Grenoble Alpes, CNRS, Grenoble INP*, Institut Néel, 38000 Grenoble, France

Context and Challenges

Micro-sized GaN/InGaN LED (μLED) seem to offer very promising properties adapted to display applications. However, huge luminescence efficiency decreases have been observed for μLED , presumably attributed to etching related sidewall defects states. The μLED high perimeter to surface ratio is responsible for an increased sensitivity to the SRH associated recombinations². Since SRH recombinations mainly occur in LED stack layers with high hole and electron concentration overlapping, this paper deals with X-ray photoemission (XPS) and wavelength dispersive X-ray fluorescence (WDXRF) characterizations of $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ surfaces after chemical treatments followed or not by atomic layer deposition (ALD) of Al_2O_3 .

Main results

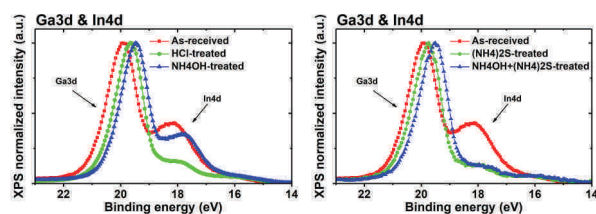


Fig.1. InGaN XPS spectra after HCl, NH_4OH or $(\text{NH}_4)_2\text{S}$

The quantitative analysis extracted from XPS spectra of fig.1 reports an indium atomic concentration decrease about 10%, 60% or 80% respectively after NH_4OH , HCl or $(\text{NH}_4)_2\text{S}$ treatments. The gallium seems rather quite stable. A decrease of oxygen levels is also observed (from 20 to 50% of decrease depending on the preparation), but never matched the indium decrease amplitude. Thus, HCl and $(\text{NH}_4)_2\text{S}$ surface treatments seem to induce indium preferential etching or desorption at the surface, whatever its oxidation state. Considering LED structures, a larger gap could act as a potential barrier for charge carriers.

The sulfur is also expected to passivate the surfaces, preventing InGaN atoms from re-oxidizing after treatments; it is however hardly detected by XPS measurements. Based on WDXRF measurements whose sensitivity is slightly higher than XPS, the sulfur dose after $(\text{NH}_4)_2\text{S}$ is evaluated at $\sim 1\text{--}4 \cdot 10^{14}$ at. cm^{-2} atomic surface density, which is not negligible in comparison with the InGaN atomic surface density presumably around $\sim 10^{15}$ at. cm^{-2} .

As illustrated by the fig. 2, the ALD of Al_2O_3 with H_2O reactant (weak oxidizer) does not seem to induce a strong modification of the InGaN surface oxidation state, since the trends observed previously for gallium and indium are quite similar.

RELATED PUBLICATIONS:

[1] C. Le Maoult et al "Analysis of InGaN surfaces after chemical treatments and atomic layer deposition of Al_2O_3 for μLED applications" Proceedings Volume 11280, Gallium Nitride Materials and Devices XV; 112801C (2020) <https://doi.org/10.1117/12.2544787>

Event: SPIE OPTO, 2020, San Francisco, California, United States

[2] Olivier, F., Daami, A., Licitra, C. and Templier, F., "Shockley-Read-Hall and Auger non-radiative recombination in GaN based LEDs: A size effect study," Appl. Phys. Lett. 111(2), 022104 (2017)

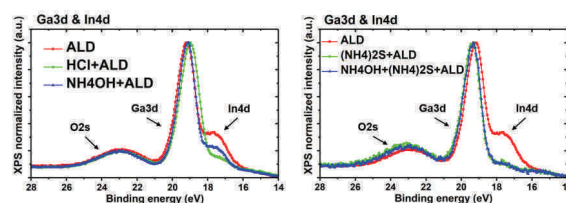


Fig. 2. InGaN XPS spectra for ALD samples with or without surface treatment

WDXRF-based counting measurements after the first TMA cycles were also performed in order to indirectly evaluate the surface proportion of OH related species by TMA grafting (fig. 3). The HCl or especially $(\text{NH}_4)_2\text{S}$ treatments seem to induce a slight inhibition of the initial growth regime. On the contrary, NH_4OH treatments seem to promote hydrolysis of InGaN surfaces and probably a better nucleation of Al_2O_3 thin layer during first ALD cycles, opening presumably the way to a very good coverage of InGaN surface.

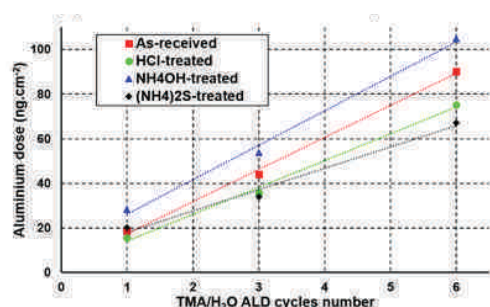


Fig. 3. WDXRF quantification estimation of the aluminum dose on the InGaN surfaces after 1, 3 or 6 TMA(1st)/ H_2O ALD cycles with or without surface treatment

Perspectives

Complementary WDXRF investigations of Al_2O_3 deposition on sulfur treated surfaces would now be of tremendous interest in order to evaluate sulfur bonds stability depending on the oxidizing nature of deposition processes. This study also underlines behavior differences between indium and gallium through the studied surface treatments. Thus, an efficient passivation process will need to handle the sensitive oxidation state of indium, while providing efficient solution to passivate gallium atoms, rather quite stable. Additionally, electrical characterization such as C-V or DL(O)TS are required to correlate these qualitative observations with electrically active interface defects, especially to identify the most sensitive defects and consequently the most efficient surface treatments.

Development of high brightness full color micro-displays: assessment of the potential of Gallium Nitride-based technology.

RESEARCH TOPIC:

High luminance LED Micro-display, color conversion, CMOS IC.

AUTHORS:

E. Quesnel, A. Lagrange, M. Vigier, M. Consonni, M. Tournaire, V. Le Marchand, A. Suhm, P. Demars, J.C. Pillet, B. Ben Bakir, N. Olivier.

With the development of augmented reality (AR) application market, there is an increasing demand for very bright full color micro-displays. These displays are challenging to manufacture and require innovative photonic technologies. Among them, the GaN-based emissive display technology is seen as the most promising one. In the present work, the complete manufacturing process flow of a full color GaN-based micro-display has been investigated from the design of the electronic CMOS driving integrated circuit, to the pixel processing and color generation process. On this basis and thanks to a dedicated modeling approach, a realistic prediction of the potential of this emissive GaN-based micro-display technology could be done. It shows that with current material and CMOS-integrated circuit performance available at CEA-Leti, white video images with luminance exceeding 100.000 cd/m² could be displayed.

SCIENTIFIC COLLABORATIONS: NOVAGAN, NEXDOT, MICROOLED, THALES AVIONICS.

Context and Challenges

While projectors and cameras have been dominating the micro-display market so far, the future market should be driven by micro-displays in Head Mounted and Head Up Display applications. Today, the popular AR headsets suffer from lack of luminance to allow the display of readable information, in particular for avionics or automotive use. To take up this challenge CEA-Leti has been developing for several years [1] a complete high brightness micro-display technological process flow from the design of CMOS driving circuit, to the pixel processing of GaN epi-wafers and further integration of color conversion solutions. More recently, in the framework of the H2020 HILICO project [2], a thorough evaluation of the real potential of such technology has been done taking into account realistic integration scenarios as well as material performances.

Main Results

The chosen RGB display technology implemented at CEA-Leti involves 3 main technological levels of integration, the silicon-based CMOS control integrated circuit (IC) with two successive stacking on top of it, the GaN micro-LED array and the conversion layers. Each level is characterized by key parameters to be controlled to ensure the display of high brightness full color video images (Fig. 1).

The first level consists in the CMOS IC which was specifically designed to monitor a (1640x1033) 9.5-μm-pitch pixel array. After optimization, an IC architecture able to deliver at pixel level current/bias voltage up to 20μA/4V was designed with a total electric power of 3W. Starting from a 8-inch CMOS wafer, the two other technological levels require sub-micron alignment accuracy; hence working on a microelectronics manufacturing line. In this regard, the transfer of micro-LED array followed by individual electrical pixel connection was successfully demonstrated using a metal-to-metal direct bonding technique. 3% electro-luminescence quantum efficiency (η_{EL}) was measured at pixel level but up to 9% was demonstrated on optimized epilayers (Novagan). For the color conversion level two approaches were investigated involving either semiconductor nanocrystals (Quantum Dots (QDs)) embedded

in a photo-patternable resist or transfer of quantum wells epilayers. While this second route still needs further development, implementation of QD-based route with the support of Nexdot partner already demonstrated $\eta_{PL}=30\%$ blue-to-red color conversion rate and a pixel patterning capability on GaN epilayers down to 5μm resolution.

On the basis of these technological achievements, a micro-display integration scheme based on realistic CMOS IC and material performances, was evaluated considering that each white pixel is made of 4 elementary pixels arranged in a RRGB configuration to limit and balance the blue radiant powers to be produced at the level of the different blue micro-LEDs. Detailed calculations recently published [3] show that with the CMOS IC designed by CEA Leti, white images could be displayed in video mode (20% of lit on pixels) with particularly high luminance exceeding 100.000 cd/m².

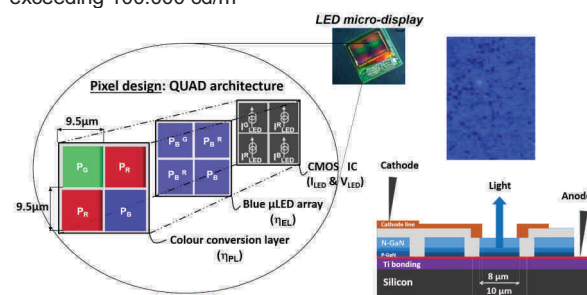


Fig. 1. Integration scheme for a full RGB (Red/Green/Blue) micro-display. Example of emitting 10μm-pitch blue micro-LED array after transfer onto a silicon interposer.

Perspectives

So far, the technological levels of integration have been tested separately. After reception of first CMOS IC wafers based on CEA-Leti design, the next step will be to demonstrate the full manufacturing of bright RGB GaN-based micro-displays and their integration into a dedicated optical combiner to build an AR headset for avionics application (partnership with THALES).

RELATED PUBLICATIONS:

- [1] F.Templier et al.; High-resolution, active matrix, 10-μm pixel-pitch GaN LED micro-displays for Augmented Reality applications; SPIE Proc. Vol. 10556. 2018. <https://doi.org/10.1117/12.2294527>.
- [2] HILICO: High Luminance in Cockpit. Clean Sky's HiLiCo: Bright ideas take flight. Available: <https://www.cleansky.eu/clean-skys-hilico-bright-ideas-take-flight>
- [3] E.Quesnel et al.; Dimensioning a full color LED microdisplay for augmented reality headset in a very bright environment; J Soc Inf Display. 2020;1-14. <https://doi.org/10.1002/jsid.884>

Challenges and solutions for high-performance GaN MicroLED displays

RESEARCH TOPIC:

Solutions and new concepts for high-performance, large-area, GaN-based MicroLED displays.

AUTHORS:

François Templier, Jeannet Bernard, Helge Haas, S. Caplet, Alexis Bédoin, Myriam Tournaire, Patrick Peray

We discuss the main challenges for the fabrication of emerging MicroLED displays. We show that microtube technology is very well adapted to these new kind of displays, since it provides both mechanical and electrical connection of the MicroLEDs on the receiving substrate. In addition, we present a new fabrication approach, where elementary units consisting of all-in-one- RGB MicroLEDs on CMOS driving circuit are transferred onto a substrate. This new concept improves the driving performance, simplifies the fabrication process, and opens a wide range of new applications.

Context and Challenges

MicroLEDs have attracted a strong interest for direct view displays, where they promise outstanding image quality and better energy efficiency comparing to existing display technologies. However, today microLEDs displays products are not commercially available, due to an addition of significant technical challenges [1]. Here we present two key solutions provided by LETI to overcome these difficulties.

Main Results

To fabricate such displays, in a classical approach, Blue, Green and Red microLEDs are manufactured. Then they are singulated and transferred onto the TFT backplane. A first difficulty is to ensure both mechanical and electrical connection of each microLED. In existing technologies, these features are made at two different steps. Therefore a solution where mechanical and electrical bonding of the MicroLEDs are made in a single step is highly desirable. LETI has developed the microtube technology where in a single operation at room temperature both mechanical and electrical connections are made. Here we show that it can be applied to fabricate microLED displays [2]. We have fabricated 25- μm size Blue, Green and Red microLEDs, on top of which connection pads have been made. On the other side, driving circuit were fabricated, and on each contact microtube where grown. After transfer on the circuit, microLEDs could be switched on successfully (Figure 1).

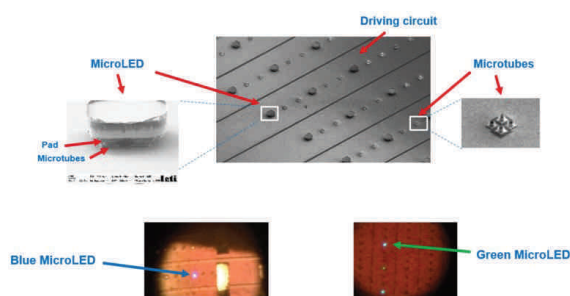


Fig. 1. Display prototype showing operation of microLEDs connected with microtube technology.

This result shows that microtube technology appears to be a very suitable solution for microLED displays.

Another challenge of microLED displays is the electronic driving. For example, high current levels are needed. Also, GaN-based microLEDs are quite inhomogeneous, and therefore complex driving schemes are needed to compensate these non-

uniformities. Existing TFT technology will not fulfill these requirements. LETI proposes a new approach for fabricating MicroLED displays, which combines CMOS driving and simple transfer process [3]. The key idea is to fabricate a series of elementary units and transfer them onto a receiving substrate containing only lines and columns (Figure 2). Each elementary unit consists of all-in-one- RGB MicroLEDs on CMOS driving circuit.

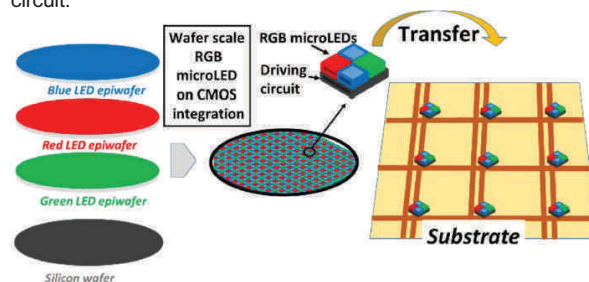


Fig. 2. New approach where an elementary unit of RGB LEDs on CMOS driving circuit is fabricated and transferred.

The first advantage of this approach is on the performance side: CMOS driving provides the best device performance, highest integration, and therefore it is the best solution for the demanding driving circuits required by the microLED displays, and as a result, best display performance. Another strong advantage is that the receiving substrate is no more a TFT backplane, but a simple substrate with only columns and lines. This opens possibility of cheaper substrate (no need for photolithographic steps), freedom of material (flexible, transparent, ...), no display size limitation (get rid of present TFT limitation at GeN10) and finally opens a wide range of new applications.

Also, the transfer step itself needs only one transfer per pixel, instead of three or four, which corresponds to a strong reduction in processing time.

Perspectives

We have proposed a new approach where elementary units consisting of all-in-one- RGB MicroLEDs on CMOS driving circuit are fabricated and transferred on simple receiving substrates. The driving performance is improved, which means better image quality. Also, the transfer (pick-and-place) process is improved with a drastic reduction of transfer steps. This approach is paving the way to ultra-high quality microLED displays, and could also provide a wide range of new applications together with new industrial models.

RELATED PUBLICATIONS:

- [1] F. Templier, "Challenges and solutions for High-performance GaN MicroLED displays", Invited Paper, Proc. Of International Conference on Display Technologies ICDT'19, Kunshan, China, 26-29th March 2019 (2019).
- [2] J. Bernard, H. Haas, S. Caplet, A. Bédoin, M. Tournaire, P. Peray, "MicroLED Displays based on Transfer with Microtube Interconnections", SID Digest 2019; Display Week, San José, 12-17 May 2019 (2019)
- [3] F. Templier and J. Bernard, "A New Approach for Fabricating High-Performance MicroLED Displays", submitted to Proc. Of Society for Information Display Conference 2019 (SID'19), San Jose, 12-17 May 2019 (2019)

Design considerations for holographic retinal projection display

RESEARCH TOPIC:

Augmented Reality, Fourier Optics, Holography, Sparse Aperture Imaging

AUTHORS:

Christophe Martinez, Fabian Rainouard, Basile Meynard, Matthias Colard

We present design considerations for the development of a retinal projection display based on the association of a photonic integrated circuit and a pixelated hologram. Unexpected behavior concerning the randomness distribution of the emitting elements in our display is highlighted.

SCIENTIFIC COLLABORATIONS:

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Pr Edouard Oudet, Laboratoire Jean Kuntzmann, Université Grenoble Alpes, Bâtiment IMAG, BP 53, 38041 Grenoble Cedex 9

Context and Challenges

CEA Leti has introduced in 2018 an innovative concept for Augmented Reality applications [1]. It consists in a display that directly emits a wavefront that forms an image on the retina. The use of a combination of integrated photonics and holography in this concept is expected to alleviate the current constraints on the see-through, near to eye device compactness.

The imaging process on the retina is based on a disruptive concept of self-focusing similar to sparse aperture imaging. It consists in introducing a degree of randomness in the spatial distribution of a group of emitters associated to one image pixel. We have demonstrated experimentally the capability of random aperture distribution in the imaging process [2]. Figure 1 shows experimental results for periodic, random and quasi-random Emissive Point Distribution (EPD). Our next objective is to determine a realistic and efficient EPD consistent with our device manufacturing. For that purpose, we have analyzed the imaging performance as a function of a randomness coefficient ρ .

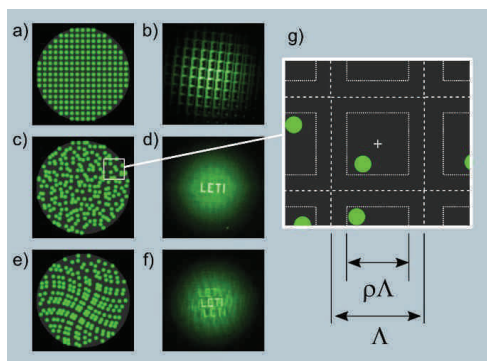


Fig. 1. Examples of EPD (a,c,e) and of the experimental imaging results (b,d,f) [2] and description of the ρ coefficient for a quasi-random EPD defined on a Λ grid [3].

Main Results

We evaluate the imaging performance through the Signal to Noise Ratio (SNR) of the point spread function of the system. It is the ratio between the intensity of the central peak and of the first secondary peak. The maximum value of the SNR given by the Airy function is 17,6 dB.

We show in figure 2 the results of simulations on 30 random draws for each random coefficient [3]. Reducing the definition of the periodic grid Λ improve the SNR as the size of the EPD is increased. Surprisingly we observe that for intermediate periodic grid values a maximum SNR can be reached for partial EPD randomness. Typically, an optimum SNR can be reached for $\rho = 0.65$ and $\Lambda = 400 \mu\text{m}$.

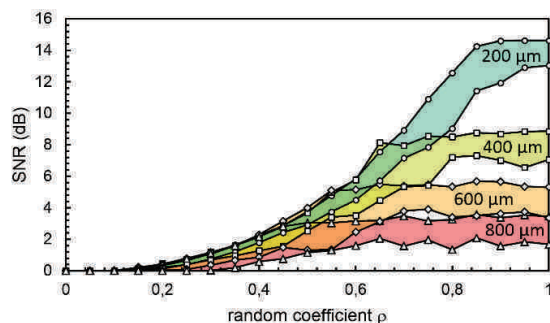


Fig. 2. Peak intensity SNR as a function of the random coefficient for various grid periods (200 μm to 800 μm) [3].

Perspectives

These results show that a full random spatial distribution with $\rho \sim 1$ is not necessarily required in our imaging process. We should have some flexibility on the EPD design without jeopardizing the imaging performance. Next objectives are now to define an integrated photonics architecture for addressing an EPD that could reach the maximum SNR identified in figure 2.

RELATED PUBLICATIONS:

- [1] C. Martinez, V. Krotov, B. Meynard, and D. Fowler, "See-through holographic retinal projection display concept," *Optica* 5(10), 1200-1209 (2018).
- [2] V. Krotov, C. Martinez, and O. Haeberlé, "Experimental validation of self-focusing image formation for retinal projection display," *Opt. Express* 27, 20632-20648 (2019)
- [3] C. Martinez, F. Rainouard and B. Meynard, "Design Considerations for Holographic Retinal Projection Display", IDW19 conference (Japan), MEET-1 (2019)

Integrated optical network design for a retinal projection concept based on single-mode Si₃N₄ waveguides at 532 nm

RESEARCH TOPIC:

SiN waveguide, integrated optics, retinal projection, visible wavelength, hologram, augmented reality

AUTHORS:

Basile Meynard, Christophe Martinez, Daivid Fowler, Engin Molva

We recently presented a novel retinal projection concept based on the combination of integrated optics and holography. Our lens-free optical system uses disruptive technologies to overcome the limitations of current devices such as a limited field-of-view and bulky optical assemblies. It uses a photonic integrated circuit (PIC) of Si₃N₄ waveguides to address projectors at the surface of a glass. The waveguides are transparent, allowing ambient light to pass through the device for augmented reality applications. This study focuses on the design of the building blocks of the PIC at $\lambda = 532$ nm: single-mode waveguides, bent waveguides, various couplers and splitters. The design of the building blocks is performed with various analytical and numerical methods (FEM, BPM, FDTD). Future work will focus on the waveguide-hologram interaction to produce images with the lens-free device.

SCIENTIFIC COLLABORATIONS: -

Context and Challenges

Augmented reality (AR) glasses partially overlap valuable digital information to the natural eyesight. It potentially allows the user to manage information more efficiently as compared to standard displays such as TV and smartphones. The concept has a large array of applications, from education, health and medical care to engineering design and automation, entertainment and many more. Our team in LETI recently presented a novel retinal projection concept for augmented reality applications [1-3]. It is based on the combination of integrated optics and holography. Our lens-free optical system uses disruptive technologies to overcome the limitations of current devices such as a limited field-of-view and bulky optical assemblies. The concept requires the design of a full photonic integrated circuit (PIC) at a new visible wavelength ($\lambda = 532$ nm) and its optical building blocks.

Main Results

Considering a PIC made using low-pressure chemical vapor deposition (LPCVD) and a working wavelength of $\lambda = 532$ nm, we use refractive indices of 2.03 for the core of the waveguide (Si₃N₄) and 1.46 for the cladding (SiO₂). The corresponding dimensions for a **single-mode waveguide** with transverse electric polarization (TE) are 300 nm (width) for a thickness of 200 nm. Losses from the curvature of the waveguide increase sharply for a radius below 10 μ m (0.05 dB/cm at 7 μ m). A distance of 1.5 μ m (center-to-center) of two parallel waveguides is sufficient to avoid cross-talk effects (coupling length > 1 m). These simulations use the finite element method (FEM). Simulations below use the beam propagation method (BPM) and 2D and 3D finite-difference-time-domain (FDTD) methods. In order to couple light in and out of the circuit, we designed **diffraction gratings**. They have a fill factor of 0.5, an etch depth of 200 nm (full etch), a period of 400 nm and 40 periods. The buried oxide (BOX) thickness is set to 2 μ m to optimize the directivity of the gratings.

We also designed a **1→2 multi-mode interference splitter** (MMI) and a 3 dB directional coupler. The MMI has a length of 3.6 μ m, a width of 1.4 μ m and a distance of 740 nm between the

two output waveguides which are enlarged to 470 nm next to the MMI core. The 3dB directional coupler has a coupling length of 5.2 μ m long and a 150 nm gap between the edges of the 2 waveguides.

The optical building blocks are fabricated by photolithography with a 150 nm resolution on 200 mm wafers. The first PIC combining several building blocks on a large waveguide array is shown in figure 1.

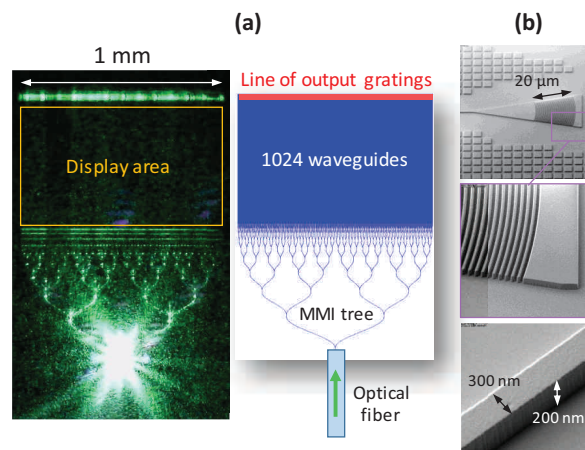


Fig. 1. a) First PIC combining several optical building blocks, with the experimental observation (left) and initial plan (right), b) SEM imagery of the input grating coupler (top) and the single-mode waveguide (bottom)

Perspectives

Future work will focus on the interaction between the waveguides and holographic optical elements (HOE). The waveguide-hologram combination will be used to provide a first experimental proof of the novel lens-free retinal display concept.

RELATED PUBLICATIONS:

- [1] C. Martinez, V. Krotov, B. Meynard, and D. Fowler, "See-through holographic retinal projection display concept," *Optica*, OPTICA, vol. 5, no. 10, pp. 1200–1209, Oct. 2018, doi: 10.1364/OPTICA.5.001200.
- [2] B. Meynard, C. Martinez, D. Fowler, and E. Molva, "Integrated optical network design for a retinal projection concept based on single-mode Si₃N₄ waveguides at 532 nm," in *Integrated Optics: Devices, Materials, and Technologies XXIII*, Mar. 2019, vol. 10921, p. 109210X, doi: 10.1117/12.2507252.
- [3] B. Meynard, C. Martinez, D. Fowler, and E. Molva, "Design of Si₃N₄ waveguides and components to form an integrated optical network for retinal projection in thin augmented reality glasses," in *Optical Design Challenge 2019*, Feb. 2019, vol. 11040, p. 1104004, doi: 10.1117/12.2523648.



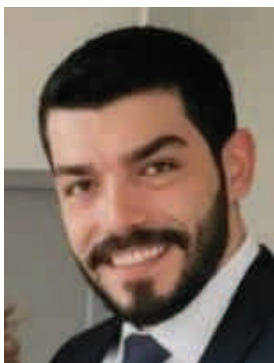
Photo ©CEA-Leti

	PhDs AWARDED IN 2019
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08

- **Houssein EL DIRANI**
- **Vera FELDMAN**
- **Nicolas LEBBE**
- **Loïc MANGIN**
- **Rami MANTACH**
- **Odran PIVOT**
- **Marion PROVOST**
- **Boris TAUREL**
- **Adrien YECHE**





HOUSSEIN EL DIRANI

DEVELOPMENT OF HIGH QUALITY SILICON NITRIDE CHIPS FOR INTEGRATED NONLINEAR PHOTONICS*Université de Lyon (France)*

Optical frequency combs have revolutionized the telecommunications field and paved the way for groundbreaking data transmission demonstrations at previously unattainable data rates. Optical frequency combs brought benefits also for many other applications such as precision spectroscopy, chemical and bio sensing, optical clocks, and quantum optics.

Silicon-nitride-on-insulator is an attractive CMOS-compatible platform for optical frequency comb generation in the telecommunication band because of the low two-photon absorption of silicon nitride when compared with crystalline silicon. However, the as deposited silicon nitride has a hydrogen related absorption in the telecommunication band. In this thesis, we report on the fabrication and test of annealing-free silicon nitride nonlinear photonic circuits.

Experimental evidence shows that micro-resonators using such annealing-free silicon nitride films are able to generate a frequency comb spanning 1300-2100 nm via optical parametrical oscillation based on four-wave mixing.

In addition, we present the further optimized technological process related to annealed silicon nitride optical devices using high-confinement waveguides, allowing us to achieve record-low losses.

Our improved Si₃N₄ platform allowed us to demonstrate on-chip integrated Kerr frequency comb sources using silicon nitride resonators that were butt-coupled to a III-V DFB laser used as a pump source. This proof of concept proves the validity of our approach for realizing fully packaged compact optical frequency combs.



VERA FELDMAN

BREAST CANCER DIAGNOSTIC SYSTEM USING SMALL ANGLE X RAY SCATTER*Université Grenoble Alpes (France)*

Current breast imaging methods, such as mammography or ultrasounds, sometimes yield inconclusive results and require a biopsy to confirm the absence of pathology. This leads to a large number of biopsies, which are invasive, stressful and time-consuming. To address this problem, new diagnostic methods, including coherent X ray scattering, are explored. Coherent X ray scattering is a promising method for improving diagnosis, as it yields information about the molecular structure of the breast tissues.

This thesis explores the use of coherent X ray scattering to refine in vivo breast tissue characterization,

as a supplementary technique, in addition to suspicious mammography. An experimental set-up for coherent X ray scattering spectra acquisition and an associated data processing methods, including classification, are proposed. The delivered dose is also studied in view of an in vivo application. The complete method is experimentally validated on plastic and biological phantoms. Obtained results are very encouraging, however improvement is still needed in order to meet clinical requirements. A few ways of improvements are suggested for the continuation of this project.



NICOLAS LEBBE

CONTRIBUTION IN TOPOLOGICAL OPTIMIZATION AND APPLICATION TO NANO-PHOTONICS*Université Grenoble Alpes (France)*

This thesis focuses on the mathematical field of shape optimization and explores two topics: one concerns the systematic determination of the design of nanophotonic components and the other one the optimal shape and location of boundary conditions defining partial differential equations (PDE).

- In the mathematical setting of the three-dimensional, time-harmonic Maxwell equations, we propose a shape and topology optimization algorithm combining Hadamard's boundary variation method with a level set representation of shapes and their evolution. A particular attention is devoted to the robustness of the optimized devices with respect to small uncertainties over the physical or geometrical data of the problem. In this respect, we rely on a simple multi-objective formulation to deal with the two main sources of uncertainties pla-

guing nanophotonic devices, namely uncertainties over the incoming wavelength, and geometric uncertainties entailed by the lithography and etching fabrication process.

- The second application concern the optimization of the shape of the regions assigned to different types of boundary conditions in the definition of a "physical" PDE. This problem proves to be difficult in the case of a Dirichlet-Neumann transition since it requires a precise study of the singular nature of PDE solutions at the transition between two regions supporting these boundary conditions. On the one hand a full mathematical study is carried out on this theoretical problem and on the other hand a numerical method based on a regularization of the boundary conditions is proposed to optimize these regions.



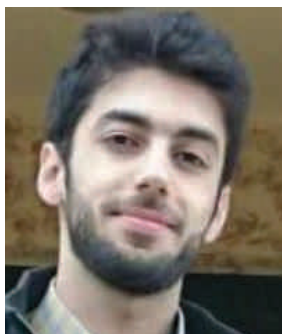
LOÏC MANGIN

STUDY AND CHARACTERIZATION OF THE PASSIVATION LAYER OF PHOTO-DIODES FOR THE OPTIMIZATION OF THE NEXT GENERATIONS OF COOLED INFRARED DETECTORS*Université Grenoble Alpes (France)*

In a context of developing the current generation of cooled infrared detectors, this work's main objectif is to improve the understanding of the passivation structure of these detectors at CEA LETI. This kind of detectors yields better performances than others available technologies, but must be cooled to cryogenic temperatures to function properly. The current developments have several objectives, augment the functioning temperature, reduce the pixel pitch, make bigger detectors with the same performances, and improve the image quality. In most of these developments, the passivation layer is known to be a factor of importance. A non-

optimized passivation layer is indeed associated with a charged state, coming from different contributions within the layer and at its interface with the semi-conductor. This charge depends on the passivation structure, the fabrication of the detector and the experimental conditions. It influences the performances of the pixels.

This PhD work has developed tools to characterize and model the passivation layer of the structures used at CEA LETI. The link between the electrical properties of the layer and the associated process flow has also been studied, as well as how the passivation properties experimentally interact with the rest of the device and degrades the performances of the detector.



RAMI MANTACH

GROWTH OF SEMI POLAR GAN (10-11) ON SILICON ON INSULATOR SUBSTRATE SOI*Université Côte d'Azur (France)*

The epitaxial growth of III-N semiconductors in non-or semi-polar orientations avoids the effects associated with the existence of internal fields in GaN-based hetero-structures usually epitaxial in the c direction. The thesis work is part of the search for ways to optimize the crystalline structure of the epitaxial layers in semi polar directions $\langle 10\text{-}11 \rangle$ on silicon substrates disoriented by 7° with respect to the direction $\langle 001 \rangle$. The original solution we have developed is to use SOI substrates for which the upper layer of Si (above the BOX) is disoriented by 7° with respect to the $\langle 001 \rangle$ direction and is as thin as possible, reducing by makes the impression of the substrate. Optimization of both the substrate structuring process and the growth stages allowed us to reduce the emerging dislocation density in GaN $\langle 10\text{-}11 \rangle$ semipolar layers by a factor of 10 compared to

state of the art on Si substrate. The residual stress, in tension when on Si, is here almost zero. We also show that the use of the so-called "Aspect Ratio Trapping", implemented for cubic symmetry materials is directly applicable to the case of semi-polar nitrides (which are of hexagonal symmetry) when epitaxied on SOI, causing another factor 10 in the reduction of the density of dislocations. We used these semi-polar low-density dislocation layers to make metamorphic InGaN layers, that is to say elastically relaxed and whose misfit dislocations are aligned along the interface. Stress relaxation allows for greater incorporation of indium for the purpose of producing longer wavelength diodes. In this sense, we demonstrate the realization of the first semi-polar LED made on SOI substrates.

ODRAN PIVOT

SCATTER CORRECTION FOR SPECTRAL COMPUTED TOMOGRAPHY*Université de Lyon (France)*

Scattered radiation is a major cause of bias, loss of contrast and artifacts in x-ray computed tomography (CT). Many correction methods have been proposed for conventional CT (using energy-integrating detectors) but it is still an open research topic in the field of spectral CT, a novel imaging technique based on the use of energy-selective photon counting detectors.

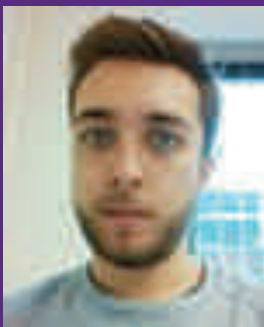
The main objective of the present thesis was to investigate scatter correction techniques adapted to spectral CT. The chosen solution refines a scatter correction method developed for integration-mode CT which uses a semi-transparent primary modulator mask. The attenua-

tion of the primary modulator mask is first compensated for with a correction matrix which takes advantage of the spectral information. The accuracy of the correction matrix, the scatter model and the whole proposed scatter correction process were tested on simulated data considering photon counting detectors with various numbers of energy bins and have shown a significant bias reduction, contrast enhancement and artifact removal. Physical experiments were performed using a parallel fan-beam set-up with a commercial energy-resolved detector. The method was successfully validated in the case of two phantoms dedicated to medical image quality measurements, with a remarkable improvement.

**MARION PROVOST****SOLGEL HYBRID LAYERS INTEGRATION IN THE PASSIVATION STRUCTURE OF OLED DEVICES***Université Grenoble Alpes (France)*

The materials and substrates used in OLED (Organic Light Emitting Diode) technology for displays allow to develop lightweight, compact and even foldable displays, demonstrating an excellent image quality and fast refresh rates. Currently, the technological drawbacks restricting the exploitation on industrial scale mainly concern the lifespan of the devices. Materials used in OLED architecture are highly sensitive to moisture and oxygen ingress and require a high barrier encapsulation. In addition, the devices should be secured from mechanical failures. Typically, glass lids and flexible barriers are used. This work deals with the OLED microdisplays deposited on silicon substrates, and aims to develop an alternative packaging solution, based on organic-inorganic nanocomposite layers, both on top and embedded into the multi-barrier passivation architecture previously developed at the CEA-LETI. Synergistic properties can be obtained

from composite materials, enhancing the advantages of both the organic (flexibility, processability) and inorganic phase (barrier properties, mechanical and chemical resistance). As a high control on the morphology is required, the sol-gel process was therefore selected for its versatility. Several composite materials were designed. One selected formulation, based on silica nanoparticles dispersed in a polymer matrix, proved to be fully compatible with the monolithic encapsulation of OLED circuits, including, among other properties, the recovery of the electrical bonding. Passivation architectures using the composite as interface layer showed improved barrier properties as well as an enhanced durability of devices stored in warm and damp environment. Our formulation provided a sufficient protection during the overall process and handling of the displays. The main advantages are: reduced thickness, improved contrast and a prospect of flexible substrate manufacturing.

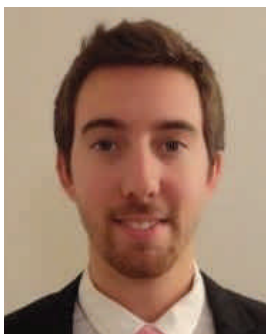
**BORIS TAUREL****THEORETICAL AND EXPERIMENTAL STUDY OF OPTICAL COUPLING IN OPTOMECHANICAL SYSTEMS***Université Grenoble Alpes (France)*

In this work, we study ring shaped suspended optomechanical resonators, and SubWavelength Grating (SWG) based optomechanical resonators.

The first approach presented – suspended ring resonators – serves as an introduction over general equations and experimental techniques. On a second approach, we propose to co-integrate SWG waveguides inside of a FabryPerot cavity. The refractive index of a SWG waveguide is periodic with a pitch way smaller than the wavelength that results in a lossless propagation with no diffraction effects. The medium can be approximated as uniform, with an averaging effect over its refractive

index. In particular, we evidence new optomechanical mechanisms arising from the SWG waveguide, and expect a strong optomechanical coupling strength.

All along the thesis, a systematic optical, mechanical, and optomechanical study of each structure is conducted, with both simplified analytical models and numerical simulations. The technological realization of the structures over 200 mm silicon wafers is presented, along with optical and optomechanical experimental characterizations.



ADRIEN YECHE

ELECTRON BEAM INDUCED CURRENT (EBIC) CHARACTERIZATION AT LOW TEMPERATURE OF THIRD GENERATION INFRARED DETECTORS

Université Grenoble Alpes (France)

Electron beam induced current (EBIC) characterizations have been performed on infrared (IR) photodetectors mainly based on HgCdTe (MCT). The EBIC setup has been developed to improve the signal to noise ratio and to address the whole IR spectrum.

Monte Carlo simulations and experiments on a dedicated pattern have allowed quantifying the EBIC spatial resolution. In contrary to observations through a passivation requesting an energy high enough to inject electrons in the active layer, typically 15 keV for a spatial resolution of around 1.4 μm , a cross section study allows to reduce the resolution to 40 nm at 2 keV. At high energy, the beam investigates the bulk material and carriers are less influenced by interface states. A change in the carrier diffusion has been observed with a diffusion length increase with increasing

the probe current for MWIR and LWIR p/n MCT at 300 and 145 K respectively. Even if the semiconductor properties are kept at low injection, a precise diffusion length determination can be obtained by a high signal to noise ratio enhanced by whether a strong probe current or a high energy. The cross section surface influence has been compared for intrinsic n/p and p/n MCT technologies thanks to top view and cross section observations. Finally, the modulation transfer function has been measured for MCT photodiodes in a matrix environment.

Unlike optical measurements, the very good EBIC spatial resolution allows to investigate the future IR detectors for pixel pitches below 10 μm





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