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TECHNOLOGY
RESEARCH
INSTITUTE

2020
SCIENTIFIC REPORT

OPTICS AND PHOTONICS

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

CEA-Leti is a technology research institute of France's CEA and a global leader in miniaturization technologies enabling smart, energy-efficient, and secure solutions for industry. Founded in 1967, CEA-Leti conducts pioneering micro and nanotechnology research and custom develops differentiating application-specific solutions for global companies, SMEs, and startups. CEA-Leti tackles critical challenges in healthcare, energy, and digital migration. From sensors to data processing and computing solutions, CEA-Leti's multidisciplinary teams deliver solid expertise, leveraging world-class pilot production lines to scale new technologies up. With a staff of more than 1,900, a portfolio of 3,140 patents, 10,000 sq. meters cleanrooms, and a rigorous IP policy, CEA-Leti has launched 69 startups and is a member of France's Carnot research network. based in Grenoble, France, the institute has offices in Silicon Valley and Tokyo. **Follow us at www.leti-cea.com and @CEA_Leti.**

Technological expertise
CEA (the French Alternative Energies and Atomic Energy Commission) is a leading global research organization whose mission is to transfer new scientific knowledge and innovations to industry. With a focus on electronics and integrated systems from micro to nano, CEA innovations make businesses in transportation, health, safety, and telecommunications more competitive by helping them develop high-performance, differentiating products and novel solutions.
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DE LA RECHERCHE À L'INDUSTRIE
cea

CEA-Leti at a glance

450
publications per year

Founded in
1967

1,904
researchers

ISO 9001
certified since 2000

Based in
France (Grenoble)
with offices in the

3,140 patents
in portfolio

114
European projects

US (San Francisco) and
Japan (Tokyo)

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

300
industrial partners

69
startups created

OPTICS AND PHOTONICS

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

- all-wavelength imaging (Gamma and X rays, visible, infrared, THz)

- optical data communications

- optical environmental and 3D sensors

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

CONTENTS

OPTICS AND PHOTONICS

FOREWORD

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Dr. Agnès Arnaud
Head of the Optics and
Photonics Division

We just lived through a very particular year. The COVID-19 pandemics halted most of production environment and cancelled most of the trade and scientific events. On the world level, we have failed, and paid the price in lives and livelihoods lost in the pandemic.

Coinciding with the collapse of the globalization, the pandemic unexpectedly accelerated the slowbalisation by setting significantly higher barriers for companies to do business across the world.
Added to geopolitical rivalries, the global semiconductor supply chain has been questioned, leaning sometimes towards installing factories in the regions they are serving.

The COVID-19 crisis triggered unprecedented policy responses across Europe and the globe. Luckily, the government funding in Europe did not dry. National recovery and resilience plans were put in place. The much needed government support was provided at a substantial level, particularly in France.
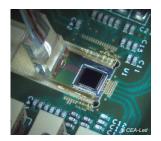Furthermore, the pandemic acted as an accelerator of digitalization, and the high-tech sector seized its opportunity.

From the initial sequencing of SARS-CoV-2 and the ultraviolet LEDs used in air filtration to spectroscopy-based diagnostic tests like real-time PCR, optics and photonics enabled the fight against COVID-19. And optical tele- and data-coms continued to flourish.

At CEA Leti, we have developed resilience and showed innovation in our response to the challenge. We learned to connect and work through virtual meetings. We renewed our connections to our partners and customers, and we saw our partners bouncing back as well, showing innovation and resilience. Today, we anticipate a sound post-covid recovery and look into the new future with confidence and optimism.

The report you are reading represents our open publications of the last year, a year although unusual, but finally not so different from the previous ones in terms of scientific results.

KEY FIGURES

345 persons overall total workforce

235 permanent R&D engineers and technicians

43 CEA experts

45 PhD students and post docs

74 patents filed in 2020

700 patents in portfolio

20% under licensing contract

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

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

Integration and packaging
Material, optical and opto-electronic characterization facilities
Advanced means of modeling and simulation

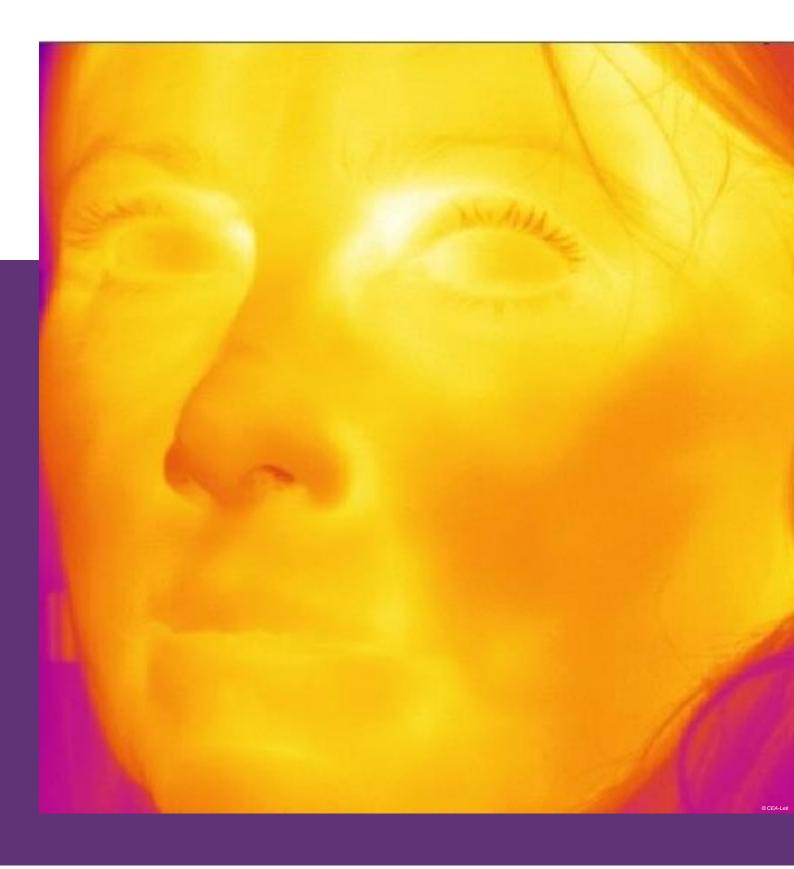# SCIENTIFIC ACTIVITY

Publications

96 publications in 2020 including
40 papers in peer reviewed journals

Prize and awards

François Templier: 2021 Fellow Award from Society for Information Display
Etienne Quesnel et al.: Best paper award at Eurodisplay 2019 for "Dimensioning a full color LED microdisplay for augmented reality headset in a very bright environment"
https://onlinelibrary.wiley.com/toc/19383657/2021/29/1

Scientific committees

Technical Program committees of: SSDM, ECOC, Display Week, ICDT, IDW, IEEE NSSSMIC, ADTC, Electronic Imaging, IEEE Photonics Summer Topicals, GADEST, ECTC, ESTC, OPTRO, ESSCIRC, IWDSC, NDIP.
Members of the IRDS roadmapping initiative, AFNOR French standards body.

O1

IR IMAGING:
II -VI COOLED

- **In HgCdTe SWIR imager, pixel geometry influences the persistence**

- **Space-radiation-induced degradation of the image quality of HgCdTe detectors is understood and mitigated**

- **In single-carrier multiplication, the speed of HgCdTe avalanche photodiodes is limited only by the transition time of the carrier**

- **HgCdTe avalanche photodiodes detect data at 625 Mbps**

- **Alloys allow very-low-t° assembly of small-pitch HgCdTe imagers**

Persistence and dark current characterization on HgCdTe Short Wave Infrared imagers for astronomy at CEA and Lynred

RESEARCH TOPIC:
Persistence, SWIR imager, HgCdTe, astronomy

AUTHORS:
T. Le Goff, N. Baier, O. Gravrand, O. Boulade, T. Pichon

In the frame of the Astronomy Large Format Array for the near-infrared ("ALFA-N") technology development program, dark current and image persistence are under investigation on test detectors. We propose a dedicated test protocol in order to electrically characterize persistence and an empirical modelling tool to describe it in terms of amplitude and time decay. From a reproducible reference point, the dark current, this protocol is applied on detectors manufactured in LETI clean rooms and aims at a better understanding of the phenomenon. Using an array containing different diode flavours (ie variations in the technological parameters), we show that the pixel geometry has a large influence on persistence, leading to future manufacturing improvements.

SCIENTIFIC COLLABORATIONS: CEA-Leti and CEA-IRFU.

Context and Challenges

Despite the growing demand for large format arrays for infrared detection in astronomy, there is no manufacturing line in Europe for such detectors. As a response to this context, the Astronomy Large Format Array for the near-infrared ("ALFA-N") technology development program aims at setting up the fabrication of very large IR focal plane arrays (FPA) for astronomy needs in Europe. High performance requirements such as low read-out noise (18e-), high quantum efficiency (80%) and low dark current (0.1e-/s) at 100K have already been demonstrated at LETI but in a smaller TV format.
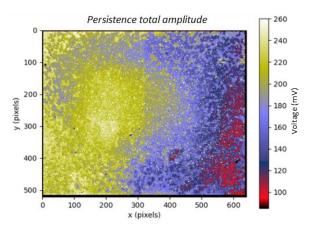
Main Results

However, the performance in terms of persistence of these detectors is still unknown. After a bright exposure, short wave infrared imagers for astronomy exhibit an excessive non-linear signal whose time constant is compatible with the integration time used in this application. This persistence limits the performances of the imager and leads degraded operating conditions. In addition, there is yet no consensus on how to characterize this phenomenon in the literature, each team performing a protocol according to the needs of its specific mission. The objectives of this study is consequently to develop a persistence characterization protocol for a better understanding of this phenomenon and to transfer this knowhow for future characterizations on ALFA. We use test detectors from LETI clean rooms, including a multi-geometry focal plane array to study physical mechanisms involved on persistence and related technology modifications.

Perspectives

Since persistence is the result the detector history, including previous illumination or voltage change, we first had to setup a protocol to reset this signal between two measurements. We get dark current performance close to the state of the art, with 0.025 e-/s/pix at 100K and no influence of the pixel geometry. We then characterize persistence with an electrical stress procedure. Though not representative of real astronomy observations, this protocol has the advantage to be easier to carry out than a light stimulation. It only consists on applying a steep voltage change on the detector and follow the pixel response after this stimulation. This procedure reveals large non-uniformities over a single array, which are not investigated with classical measurements such as dark current or pixel capacitance. This protocol is therefore relevant in a manufacturing line to probe second order technological parameters. Concerning pixel geometry effect, large metallization size shows fewer persistence amplitude, shorter time constant and fewer non-uniformities. Finally yet importantly, diode implantation has less influence on persistence than the non-uniformities. Consequently, persistence mechanisms should be the result of surface or pixel capacitance variation instead of bulk trap emission processes. We are now developing a new test setup using low light stress to provide a test procedure closer to real operation conditions.

Persistence amplitude mapping after a 900mV voltage stress.

RELATED PUBLICATIONS:
[1] T. Le Goff, N. Baier, O. Gravrand, O. Boulade, T. Pichon, "*Persistance and dark current characterization on HgCdTe short wave infrared imagers for astronomy at CEA and Lynred*", Proc. SPIE 11454, 114541K (2020); doi:10.1117/12.2560338

Theoretical and experimental study of the influence of the CdZnTe substrate thickness on the response of infrared HgCdTe photodetectors under proton irradiation

RESEARCH TOPIC:
The H2020 Astronomical Large Format Array program aims to set up an ITAR-free production chain for astronomical high performance IR imagers.

AUTHORS:
T. Pichon, O. Gravrand, G. Badano, O. Boulade, Salima Mouzali, O. Limousin

Proton induced luminescence may be very detrimental for imaging retina for low flux astronomy in the IR. Indeed, it may strongly degrade the image quality, inducing hot spots due to the energy deposited by the proton pass when the sensor is used in a space observatory. We demonstrated that this phenomenon is limited by the CZT substrate used for such HgCdTe imaging devices. When thinned, the image degradation may be limited to only the direct neighbouring pixel around the proton trace. An experimental irradiation campaign involving LETI made detectors with two different substrate thickness has confirmed theoretical computations using Geant4 and homemade photon propagation and electron transport codes.

SCIENTIFIC COLLABORATIONS: PhD in collaboration between CEA-Leti (Grenoble) and CEA-IRFU (Saclay), Irradiation performed at Arronax (Saint Herblain, France)
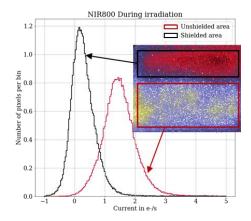
Context and Challenges

IR Astronomy is very demanding in terms of ultra-high performance IR imaging. LETI in collaboration with Lynred is currently developing MCT IR detectors for such needs. The dark current is so low (<0.1e/s/pixel) that space radiations may induce artefacts degrading image quality when used on board a space observatory. Within a transverse PhD work between CEA-LETI and CEA-IRFU, we modelled and characterized this phenomenon, showing that the proton trace is radially limited to 20nm and affects mostly the CZT substrate used for IR HgCdTe fabrication. The energy deposited in this trace induces hot charges that relax in the semiconductor then diffuse in the detector structure. Carrier diffusion as well as propagation of radiated photon during relaxation may then spread and affect several 15µm pitch pixels, degrading the image quality.
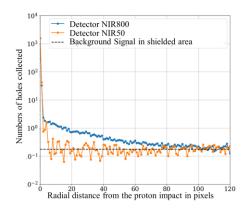
Main Results

Different detectors with different substrate thicknesses were fabricated at LETI and irradiated with 36MeV protons. The detectors were cooled at 78K and operated during the irradiation. The proton flux was chosen low enough to see individual proton impacts onto the dark flat field of the detectors.

Perspectives

A strong difference between 50µm and 800µm thick substrate was observed. The analysis of the mean impact corroborates the computations: the dominant spreading effect is due to induced luminescence rather than charge diffusion. Therefore, a production compatible substrate thickness (less than 50µm) is compatible with the operation of such detectors in space.

Raw output of the thick substrate detector

Mean Impact profiles for both detectors

RELATED PUBLICATIONS:
[1] T. Pichon, O. Boulade, S. Mouzali, P. Mulet, S. De Camillis, C.I Koumeir, Je.L. Santailler, G. Badano, O. Gravrand, and O. Limousin "Experimental study of the influence of the CdZnTe substrate thickness on the response of infrared HgCdTe photodetectors under proton irradiation", Proc. SPIE 114540O (2020); https://doi.org/10.1117/12.2562142
[2] T. Pichon, S. Mouzali., O. Boulade, O. Gravrand, and O. Limousin, "Influence of the CdZnTe Substrate Thickness on the Response of HgCdTe Detectors Under Irradiation: Modeling of the Substrate Luminescence". Journal of Elec Materi 49, 6918–6935 (2020). https://doi.org/10.1007/s11664-020-08237-0
[3] Thibault Pichon, Thèse 2020, "Modélisation et caractérisation expérimentale du phénomène de luminescence induit par l'irradiation de protons dans les détecteurs IR HgCdTe en environnement spatial"

Observation of carrier transition time limited bandwidth in single carrier multiplication HgCdTe APDs

RESEARCH TOPIC:
Study of the ultimate performance and physics of HgCdTe APDs for photon starved applications such as free space optical communications.

AUTHORS:
J. Rothman, A. Dumas, S. Pes, J. Abergel (Leti/DPFT), S. Gout (Leti/DPFT), X. Baudry (Leti/DPFT), P. Ballet (Leti/DPFT), J.-L. Santailler (Leti/DPFT), S. Renet, A. Vandeneynde, L. Mathieu, J. Le Perchec, G. Badano, T. Ligozat

HgCdTe avalanche photodiodes (APDs) offers a unique opportunity to detect low photon number signals with a minimal loss of amplitude and temporal information. This has been attributed to single carrier multiplication (SCM), that gives a credible explanation to the low multiplication noise and high gain, in excess of 100, that characterize such detectors. SCM do also imply a specific shape of the response time in APDs when it is limited by the carrier transit in the junction. The first observation of this specific shape has been obtained in in HgCdTe APDs at CEA/Leti. It gives a direct experimental observation of the SCM characteristics of HgCdTe APDs and confirms the perspectives for high data rate and low timing jitter applications, for down to single photon signal levels.

SCIENTIFIC COLLABORATIONS: European Space Agency (ESA), French National Research Agency (ANR), LabEx FOCUS

Context and Challenges

HgCdTe APDs are presently developed at CEA/Leti for applications that requires detecting a low number of photons with a high precision in amplitude and time, such as free space optical communications, atmospheric LiDAR and quantum optical information processing. The aim of this development is the optimization of both the temporal performance of the APD, characterized by the band-width and/or jitter at single photon level, and the amplitude information conservation, characterized by the quantum efficiency, maximal APD gain and multiplication noise. The APD active area do also need to be increased to enable a high optical coupling efficiency, in particular when the APDs are used in free space optical applications.
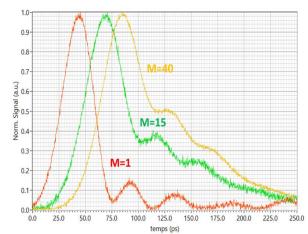
Main Results

The development of new HgCdTe APD architectures has enabled to reach a mile-stone in terms of response time characteristics for such detectors. The figure below reports the impulse response time measured at 300 K at three different values of reverse bias of the APD, corresponding to a gains of M=1, 15 and 40. At unity gain, the response time corresponds to a bandwidth of 10 GHz. This is the highest bandwidth reported so far for HgCdTe photodiodes. This observation shows that the carrier collection and charge extraction from the detector is compatible with high data rate application. It do also show that the response time jitter at the photon-counting limit, which distribution comparable to the low gain response time, can be lower than 40 ps at half maximum. An even lower jitter is expected at lower operating temperature as the electron mobility due to the expected increase in electron mobility.

At higher reverse bias, the response time is delayed and is broadened by a bump that occurs after first fast peak. This particular shape corresponds to the expected response time in carrier transit time limited SCM APDs, that was first predicted by Hayat and Saleh in 1992 [2]. The present data is the first clear observation of this behavior and gives a direct observation of the single carrier multiplication in HgCdTe APDs.

Quantitatively, the fitting of the observed response time using a numerical model allows estimating the carrier velocities in the junction during the multiplication. The estimated velocities can be used to predict the carrier transit time bandwidth limitations in APD with a narrower multiplication layer, showing on a bandwidth limitation of about 9 GHz in high gain APDs

Perspectives

The optimization of the performance of HgCdTe APDs is currently pursued with the objective to maximize the gain and bandwidth in APDs with multiplication layer area in excess of 20 μm. The latter is in favor of an increased optical coupling efficiency to the APDs and will automatically result in a higher detection efficiency. The successful development of such detectors is expected to be an enabler of applications in the fields of free space optical communications and quantum optical information processing

Impulse response time of a HgCdTe APD.

RELATED PUBLICATIONS:
[1] J. Rothman et al. To appear in SPIE Procedings of ICSO 2020 conference
[2] M. M. Hayat and B. E. A. Saleh, J. of Lightwave Tech. 10, 1415 (1992)

Close to quantum limited detection of direct optical modulation data at 625 Mbps rates with HgCdTe avalanche photodiodes

RESEARCH TOPIC:
Infrared single-photon detectors based on high bandwidth HgCdTe avalanche photodiodes

AUTHORS:
S. Pes, J. Rothman, P. Bleuet, J. Abergel, S. Gout, P. Ballet, J.-L. Santailler, J.-A. Nicolas, J.-P. Rostaing, S. Renet, A. Vandeneynde, L. Mathieu, J. Le Perchec

An in-house developed four-quadrant detection module based on HgCdTe APDs hybridized to a specifically designed Si-CMOS pre-amplifier has enabled to reach photon counting sensitivities at a bandwidth of 400 MHz. The capability of using the detector for classical free-space optical communications has been studied for direct amplitude modulated data transmission at 625 Mbps. At high APD gain, a bit error rate of 2×10^{-5} has been estimated at 12.5 photons per bit, which is only 3.9 dB above the quantum limit. This penalty corresponds to the amplitude information loss of the detector and shows the importance of maximizing the detection efficiency while reducing the multiplication noise in HgCdTe APDs.

SCIENTIFIC COLLABORATIONS: European Space Agency (ESA), French National Research Agency (ANR), LabEx FOCUS

Context and Challenges

In the last years, free-space optical (FSO) communications have attracted significant attention due to higher achievable data rates and higher power efficiency with respect to standard bulky RF-based counterparts. Among others, FSO systems find application in backhauls for global internet coverage and telecoms networks, and inter-satellite or satellite-to-ground long distance optical links. FSO links are typically established in the atmospheric near infrared transmission window. However, the detected light power and corresponding bit error rate (BER) are still limited by beam divergence, atmospheric absorption and turbulences. To sustain high transmission rates using receiving optics with reasonable complexity in terms of aperture and beam tracking, free-space coupled detectors with large area and high sensitivity able to detect a low number of photons at large bandwidths are needed.

Main Results

CEA-Leti is currently addressing such challenges by developing a new generation of optical receivers at 1.55 µm based on HgCdTe avalanche photodiodes (APDs) that are hybridized onto a low-noise high bandwidth in-house designed Si-CMOS trans-impedance amplifier (TIA). These detectors can detect optical signals down to the single-photon level, with high detection efficiency and at count rates exceeding 1 GHz. Very recently, we have explored the capability of our detector to be employed as an optical receiver for 625 Mbps data rate Return-to-Zero On-Off Keying (RZ-OOK) modulation format [1]. The results of this study show that when the detector approaches the photon counting regime at high APD gain, the BER is limited by the information conservation figure of merit of the detector, measured by the quantum efficiency to excess noise ratio (QEFR). In the present detector, this corresponds to a -3.9 dB penalty compared to the quantum limit, equivalent to 12.5 photons/bit at a BER of 2×10^{-5} (see Fig. 1). This result indicates that, for high enough APD gain, the BER is directly related to the QEFR of the detector. Hence, the BER penalty can be reduced through increased QEFR and APD gain while

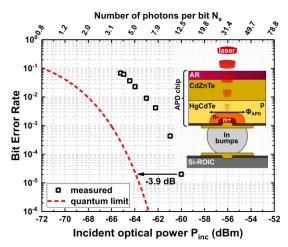minimizing the dark counts and the timing jitter of the detector.

Fig. 1: Estimated BER at 625 Mbps RZ-OOK.

Perspectives

Current efforts at CEA-Leti focus on the optimization of the HgCdTe APD technology [2], involving the development of a modified APD process with capability to form larger area diodes with more homogeneous multiplication layer that is expected to enable higher gain, lower excess noise and reduced jitter. Another important axe of development concerns the CMOS TIA. A modified design of the presently used Si-CMOS amplifier should enable to extend the bandwidth towards 1 GHz. An even higher bandwidth can be reached using SiGe Bi-CMOS technology. Finally, the use of a recently developed integrated µ-lenses array has the potential to improve the optical coupling, and should enable to further approach quantum limited detection through an increased detection efficiency to multiplication noise ratio and a reduced temporal jitter.

RELATED PUBLICATIONS:
[1] S. Pes et al., "Reaching GHz single photon detection rates with HgCdTe avalanche photodiodes detectors", SPIE Proc. of the International Conference on Space Optics 2020 (ICSO 2020), March 2021 (in press).
[2] J. Rothman et al., "HgCdTe APDs detector developments for high speed, low photon number and large dynamic range photo-detection", SPIE Proc. of the International Conference on Space Optics 2020 (ICSO 2020), March 2021 (in press).

Low melting point alloys development for photonic components assembly

RESEARCH TOPIC:
Interconnection, low melting point alloys, flip-chip bonding, infrared, microbumps

AUTHORS:
G. Desperrier, O. Mailliart, S. Renet, P.-H. Haumesser (DPFT), R. Pesci(ENSAM)

LAIP develops interconnections to hybridize photonic components. In bump is the most commonly used interconnection for cooled infrared detectors applications. It presents the advantage of a relatively low melting point (156°C) allowing joining processes at about 200°C. Nonetheless, in some cases, this joining temperature can be too high, especially in heterogeneous assemblies in which there is a mismatch in thermomechanical behaviour. The thermal expansion difference between the components might overtake the pixel pitch. In order to lower joining temperature, we developed binary and ternary In based alloys to replace pure In as a solder and managed to assemble a mechanical demonstrator at a temperature as low as 90°C.
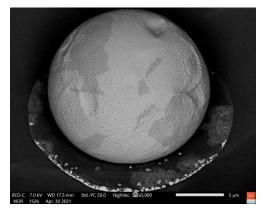
Context and Challenges

Photonic Assembly and Integration laboratory has been developing indium microbumps technology in 15 and 30 µm pitches for about 20 years. It consists in connecting mechanically and electrically the detector circuit to the ROIC at the scale of each pixel, using indium as a solder. Cooled infrared technologies use these bumps for sensitive substrates that have poor thermomechanical compatibility with silicon base. Temperature rise during assembly causes different thermal expansions between top and bottom substrates. Therefore, pixels are misaligned and mechanical stress might appear in the material during cooling down. Reducing the temperature during assembly is one of the ways studied to limit these problems.
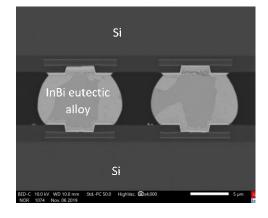
Main Results

We focused on In67-Bi33 binary alloy with melting temperature of 72.7°C and produced a mechanical demonstrator at 15 µm pitch. Six layers of In and Bi were successively deposited onto the UBM of a patterned silicon substrate using a resist mask (lift off process) to obtain a 6 µm thick bump. The melting of the bumps was observed at 72°C, which corresponds to the melting point of targeted eutectic. Hybridization of two silicon substrates was carried out in a SET FC300 flip chip bonder under reductive atmosphere at a temperature as low as 90°C.

Perspectives

We investigate other alloy compositions and other deposition processes (ECD). We aim to develop a range of solders compatible with 60°C-200°C joining temperatures.
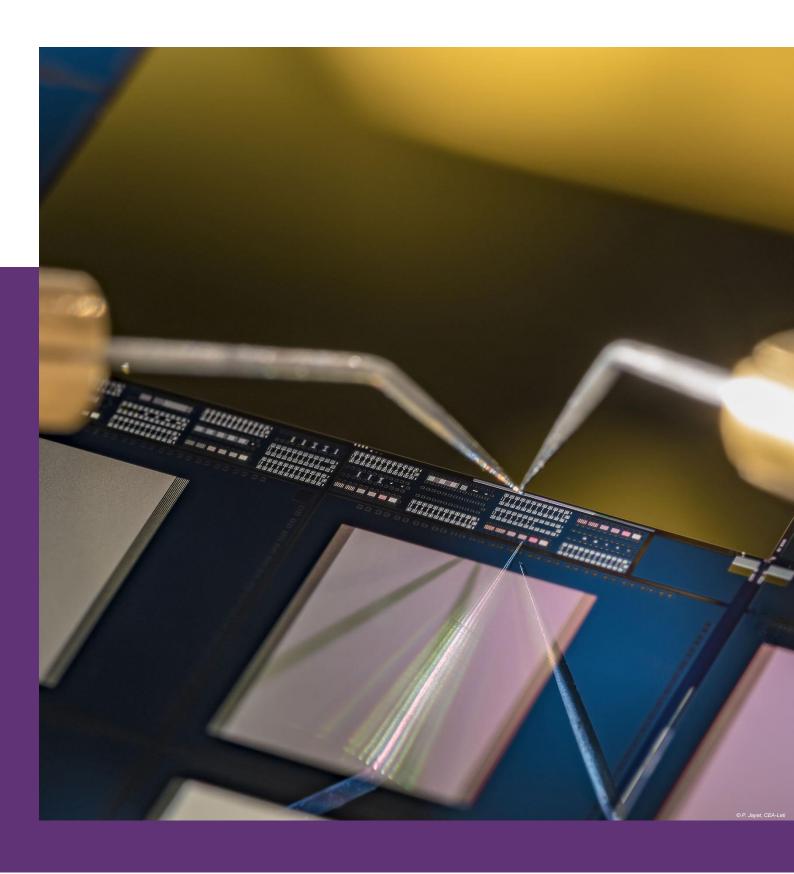

SEM picture of InBi µbump after reflow

SEM picture of two interconnections of a mechanical demonstrator at 15µm pitch. Assembly at 90°C

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O2

IR AND THZ IMAGING: BOLOMETERS

- **Cooled Silicon microbolometers for passive THz imaging**
- **Deeply cooled Silicon microbolometers detect polarization of microwave cosmic background emission**

F noise reduction in cryogenic highly compensated silicon thermistors

RESEARCH TOPIC:
Thermistors with high thermal responsivity and low noise for THz passive imaging

AUTHORS:
J. Blond, A. Aliane, J. Meilhan, H. Kaya, L. Dussopt

The thermal sensitivity and Low Frequency Noise (LFN) of compensation doped Silicon-On-Insulator (SOI) resistors are studied down to the cryogenic regime. A high compensation nominal ratio $K = N_A/N_D$ is compared with uncompensated and partially compensated configurations, using Phosphorus and Boron as dopant species. The Temperature Coefficient of Resistance (TCR) reaches -2.7%/K at 80 K, for an effective compensation ratio close to 0.98 considering incomplete dopant ionization. The measurements reveal a low LFN with a nearly frequency-independent spectrum, far from the classical *1/f* trend observed in uncompensated silicon. Such high performance thermistors represent an attractive, mature and affordable solution for high performance thermal sensing.
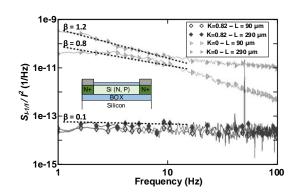
Context and Challenges

Terahertz (THz) passive imaging requires detector performances beyond the current capabilities of ambient-temperature bolometer technologies. Bolometers, cooled at liquid nitrogen temperatures (77 K) and based on silicon diode or resistive thermometers, are expected to provide improved thermal sensitivity through higher responsivity and lower noise with acceptable system requirements (size, weight, power, cost) [1][2]. The use of standard silicon technologies is also a strong asset for future commercial developments.

Main Results

Silicon thermistors are investigated as thermal sensors at 80-100 K [1]. It was shown that the compensation of dopants in silicon generates a significant Temperature Coefficient of Resistance (TCR) through their partial ionization, which is highly temperature dependent in this cryogenic regime. Dopant compensation consists in the implantation of donor and acceptor species in similar concentrations (N_A, N_D) and is characterized by the compensation ratio $K = N_A/N_D$ in the case where $N_A < N_D$.

Thermistor samples of different sizes were fabricated on Silicon-on-Insulator (SOI) wafers with a 1.5 µm silicon layer. They were ion implanted with phosphorus and compensated with boron. Dopants were activated and diffused in silicon at about 1200°C for several hours to reach a good uniformity in the thermometer volume. Compensation ratios are between 0 and 0.82 in nominal value. Taking into account the partial ionization of dopants at 80 K, the effective compensation ratios spanned from 0 to 0.98. The theoretical TCR was investigated first using numerical simulations based on established models of the literature and in particular on Altermatt's dopant energy model and Klaassen's carrier mobility model. Measurements revealed a very good agreement with the theory as a function of temperature and doping, and a TCR as high as 2.7%/K (absolute value) at 80 K for the highest compensation ratio.

The low frequency noise of these thermistors is composed of the Johnson noise, due to the thermal fluctuation of carriers, and *1/f* noise linked to mobility fluctuations. Experimental noise spectra showed that the *1/f* component was dramatically reduced in samples with high compensation ratios and this effect was weakly dependent on samples length or temperature (Figure 1). In contrast, samples with uncompensated doping exhibit a classical *1/f* spectrum.

Noise measurements at 80 K.

Perspectives

Compensated silicon thermistors demonstrated here feature attractive thermal responsivity and noise levels. The future work will extend the theoretical and experimental investigations on other dopant species and the impact of interfaces in the case of thinner silicon layers. Next, the integration of such thermistors in actual bolometers will be undertaken in the perspective of high-performance cooled focal plane arrays suitable for THz passive imaging.
Funding: French MoD and Labex FOCUS (ANR).

RELATED PUBLICATIONS:
[1] J. Blond, A. Aliane, J. Meilhan, H. Kaya, L. Dussopt, "1/f Noise Reduction in Cryogenic Highly Compensated Silicon Thermistors," *IEEE Electron Device Letters*, vol. 41, no. 12, Dec. 2020.
[2] J. Blond, A. Aliane, J. Meilhan, H. Kaya, S. Litaudon, L. Dussopt, "Thermometric SOI Lateral Diodes for Bolometric Application: Comparison between Schottky and p-i-n Diodes," *Solid State Electronics*, 2020.

Design, simulation and fabrication of highly sensitive cooled silicon bolometers for millimeter wave detection

RESEARCH TOPIC:
mm-wave and THz detectors

AUTHORS:
A. Aliane, O-A. Adami[1], L. Dussopt, L. Rodriguez[1], W. Rabaud, J-L. Ouvrier-Buffet, V. Goudon, H. Kaya, C. Vialle, J-L. Sauvageot[1], V. Reveret[1], S. Becker, A. Poglitsch[2]

This paper reports our results on the electro-thermal modelling of cryogenic silicon bolometers with pixel pitches of 500 and 1200µm designed for cosmic microwave background (CMB) polarimetric observation in 0.6 and 1.5 mm bands. These detectors aim at a high responsivity (dV/dP_{opt}) typically around 10^{11} V/W and a very low noise equivalent power (NEP) of 10^{-18} W/Hz$^{1/2}$ at 50-100 mK. At very low temperature and high bias currents, doped silicon thermometers exhibit a non-ohmic behavior described by the hot electron model (HEM). Experimental characterizations compare well with this model, which can be used to derive the simulated responsivity and NEP performances of the pixels under weak and moderate optical power (P_{opt}) illumination.

Context and Challenges

Two pixel designs, with a pitch of 500 and 1200 µm, were developed to study the temperature and polarization of cosmic microwave background (CMB) radiation in the millimeter bands (0.6 mm and 1.5 mm). The main part of the bolometer is the doped Si:P,B thermometer, which provides a high electrical sensitivity ((T/R)xdR/dT) at very low temperature (50 - 100 mK). However, under high bias currents a non-ohmic behavior occurs and decreases this sensitivity.

Main Results

Fig.1 depicts a suspended silicon bolometer with a pitch of 500 µm. The studied thermometer has a volume of 290 µm x 300 µm x 1.5 µm and a net doping (N_d-N_a) of 2.5×10^{18} at.cm^{-3} [1]. Fig.2 depicts the resistance as a function of the applied power. At low Joule power levels, the phonon temperature (T_{ph}) is close to the electron temperature (T_e) and the sensitivity is maximized at about -7 at T_{ph} = 60 mK for a power of 10^{-13} W. At high power values, T_e becomes different from T_{ph} and the so-called hot electron effect dominates leading to decrease strongly the sensitivity of about –5 at T_{ph} = 130 mK for a power of 10^{-11} W.

Perspectives

Electrical measurements of silicon thermometers at low temperature show a non-ohmic behavior under a high bias current. This non-ohmic behavior degrades the sensitivity leading to a degradation of the NEP performances [2]. A trade-off has to be found in order to enhance electro-optical performances for future developments of this type of detectors
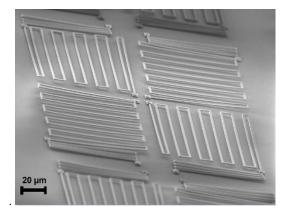

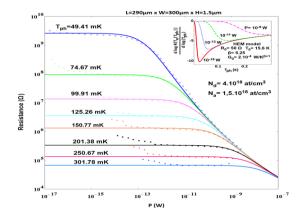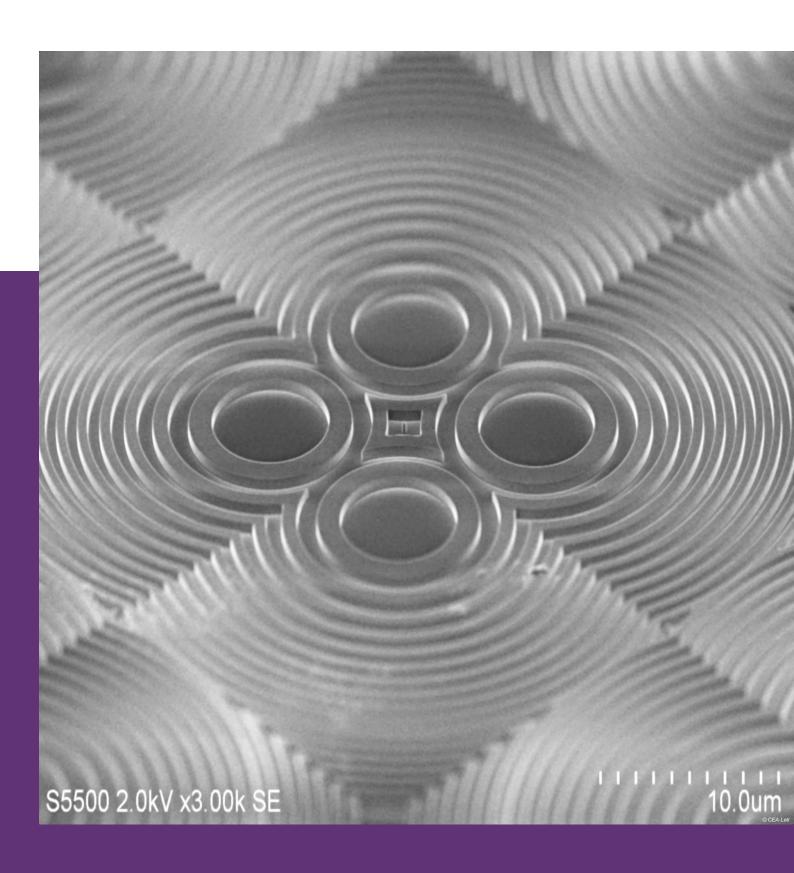**Fig.1: SEM image of a released pixel with a pitch of 500µm**

Fig.2: Electrical resistance measurements as a function of the power compared to the HEM model

RELATED PUBLICATIONS:
[1] A. Aliane et al. "Design, Simulation and Fabrication of Highly Sensitive Cooled Silicon Bolometers for Millimeter-Wave Detection". J Low Temp Phys 199, 56–64 (2020).
[2] A. Aliane et al., "Mechanichal modeling and characterization of suspended cooled silicon bolometers for sub-millimeter and millimeter waves polarization detection", Sensors and Actuators A 296 (2019) 254-264.

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O3

CMOS IMAGING

- **Planar micro-lenses makes near-IR SPAD imagers more sensitive**

- **Optimized color correction in multispectral visible –near-infrared imagers**

- **Curving CMOS image sensors improves the image quality of a camera**

- **Ultra-low-power CMOS imager wakes-up, detects movements and recognizes objects it sees**

Planar microlenses for near infrared CMOS image sensors

RESEARCH TOPIC:
CMOS image sensor, Single Photon Avalanche Diode, Fresnel zone plate ; metasurface ; microlens

AUTHORS:
L. Dilhan[1], J. Vaillant, A. Ostrovsky[1], L. Masarotto, C. Pichard, R. Paquet

Our work centers on designing a wafer level planar microlens for applications in near-infrared, on Single Photon Avalanche Diode (SPAD). New planar microlens structures were studied and designed using rigorous electro-magnetic simulation. Then, the current solution, which is the melted microlens, and two new types of planar microlenses were processed on STMicroelectronics SPAD circuit. Electro-optical characterization results and optical gain of microlens were compared to simulation results showing good agreement.
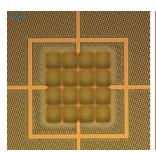
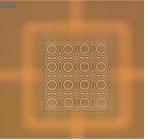SCIENTIFIC COLLABORATIONS: [1]STMicroelectronics, Crolles, France

Context and Challenges
Single Photon Avalanche Diode pixel usually present low fill-factor requiring microlens to concentrate the light on sensitive area. Traditionally, refractive microlenses formed by melted resin are used to improve the sensitivity. By increasing the degrees of freedom during the desing, for instance off-axis capability, such microlenses may outperform the standard refractive one.

Main Results
In this study, we have demonstrated the capability to improve SPAD sensitivity by using different types of microlenses in the near infrared. Considering Fresnel Zone Plate and metasurface structures, we designed microlenses based on rigorous optical simulations taking into account the SPAD layout, the CMOS technology and the current microlens solution. The current microlens solution and Fresnel Zone Plate microlens were implemented on STMicroelectronics 40nm CMOS testchips and gains of 1.9 and 1.4 in sensitivity respectively were measured compared to a SPAD without microlens.

SPAD pixels with melted microlens and FZP

Perspectives
The technologies described in this paper offer several advantages like planarization, simplicity in design and process or the capability to focus light.

RELATED PUBLICATIONS:
(1) L. Dilhan L., Vaillant J., Ostrovsky A., Masarotto L., Pichard C., Paquet R. "Planar microlenses for near infrared CMOS image sensors", Electronic Imaging, 2020, https://doi.org/10.2352/ISSN.2470-1173.2020.7.ISS-144

Color and spectral image sensors: visible and near-infrared multispectral image dataset and geometrical approach of color correction

RESEARCH TOPIC:
image sensor, color and multispectral image rendering; noise; geometry

AUTHORS:
A. Clouet, J. Vaillant (DOPT/SCIM/LIS),
D. Alleyson (CNRS/LPNC)

Color correction is a mandatory operation in color and spectral image rendering. We developed a geometrical approach, allowing the evaluation of noise propagation and amplification through this step. We derive the covariant and the contravariant SNR for noise evaluation in color reconstruction and extend this approach to spectral reconstruction for multispectral or hyperspectral images. This work was validated on our multispectral images set (ReDFISh) made available for the imaging community. This dataset covers the visible and near-infrared spectral range (400 nm to 1050 nm) and intends to provide spectral reflectance images containing daily life objects, usable for simulation of silicon image sensor.

SCIENTIFIC COLLABORATIONS: David Alleyson, Laboratoire de Psychologie et NeuroCognition, CNRS UMR 5105 Grenoble, France

Context and Challenges

Achieving nice images in low light condition is a goal for any image sensor manufacturer. Thus, many improvements have been done in noise reduction in pixel. Nevertheless, photon shot-noise still remains in raw image. Increasing the raw signal is the natural way to improve raw SNR but does not necessarily positively affect the displayed image due to color correction processing that usually tends to amplified noise natively present in the raw signal

Main Results

To address this point we chose to revisit the color correction in a an geometrical approach (1). We evaluated the non-orthogonality of spectral sensitivities and introduced covariant and contravariant SNR as a quantitative way to measure the degradation of image quality through the color correction process. This study was validated using the ReDFISh dataset (2) which contains 22 multispectral images covering the visible to near-infrared spectrum (400 nm to 1050 nm) and openly available for the imaging community.

Perspectives

The geometrical approach is also easily extendable to multispectral sensor. Therefore, future work is to optimize spectral sensitivities based on the applications and the quality metric chosen by the end-user.

Multispectral images from ReDFISh dataset

RELATED PUBLICATIONS:
(1) Clouet, A.; Vaillant, J.; Alleysson, D. "The Geometry of Noise in Color and Spectral Image Sensors". MDPI Sensors, 2020, https://doi.org/10.3390/s20164487
(2) Clouet, A.; Viola, C.; Vaillant, J. "Visible to near-infrared multispectral images dataset for image sensors design", Electronic Imaging, Material Appearance, 2020, https://doi.org/10.2352/ISSN.2470-1173.2020.5.MAAP-106

Tolerancing and characterization of curved image sensor systems

RESEARCH TOPIC:
Curved image sensors

AUTHORS:
F. Zuber, B. Chambion (INES), C. Gaschet, S. Caplet, S. Nicolas, S. Charriere, D. Henry

Curved image sensors, not having to correct the field curvature, are considered as a relevant solution for improving a large majority of optical systems. They offer the opportunity of designing compact aberration-free optical systems. In this work, we explain the advantage of the curved sensor system using the aberration theory. This work focuses on the tolerancing process of curved sensors, its inclusion in optical design and its application with curved sensors prototypes

Context and Challenges

Due to the field curvature effect, flat objects normal to the optical axis cannot be properly focused on a flat image plane. Numerous studies have demonstrated that a curved sensor improves the overall performance of an optical system in term of quality and/or compactness. We have designed a new curved-sensors-based optical system that is both compact and qualitative. Since the curved sensor may have defects, the sensor tolerancing is a new important part of the optical design.

Main Results

Due to the field curvature effect, flat objects normal to the optical axis cannot be properly focused on a flat image plane. Numerous studies have demonstrated that a curved sensor improves the overall performance of an optical system in term of quality and/or compactness. We have designed a new curved-sensors-based optical system that is both compact and qualitative. Since the curved sensor may have defects, the sensor tolerancing is a new important part of the optical design.
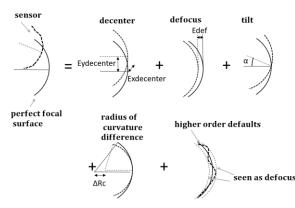

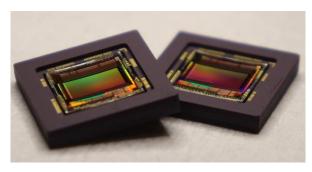**Fig. 1: Possible defects of a curved focal surface**

Fig. 2: Curved sensor prototypes

Curved sensor prototypes (figure 2) were characterized and their conformity with the specifications are discussed. Image quality is evaluated with a specific optical test bench. The results show that the sensors within the specifications significantly improve the image quality while allowing a compact lens system.

Perspectives

CEA-Leti is currently working on solutions to reduce the decenter, the sphere radius difference and the irregularities inside the curvature packaging process using an improved alignment and curvature process.

RELATED PUBLICATIONS:
[1] F. Zuber, B. Chambion, C. Gaschet, S. Caplet, S. Nicolas, S. Charrière, and D. Henry, "Tolerancing and characterization of curved image sensor systems," Appl. Opt. 59, 8814-8821 (2020)

A 3.0µW@5fps QQVGA self-controlled wake-up imager with on-chip motion detection, auto-exposure and object recognition

RESEARCH TOPIC:
CMOS image sensor, ultra-low power, motion detection, face detection, edge IA, wake-up, 1-bit processing

AUTHORS:
A. Verdant, W. Guicquero, N. Royer (LIST/DSCIN), G. Moritz, S. Martin (LETI/DSYS), F. Lepin (LIST/DSCIN), S. Choisnet (LIST/DSCIN), F. Guellec, B. Deschamps[1], S. Clerc[1], J. Chossat[1]

Analyzing image content usually comes at the expense of a power consumption incompatible with battery-powered systems. Aiming at proposing a solution to this problem, an imager with full on-chip object recognition consuming sub-10µW using standard 4T pixels in 90nm CIS technology is reported, opening the path for both wake-up and high-quality imaging. It combines multi-modality event-of-interest detection with self-controlled capabilities, a key for low-power applications. It embeds a log-domain auto-exposure algorithm to increase on-chip automation. The power consumption range from 3.0 to 5.7µW at 5fps for a QQVGA resolution while enabling background subtraction and single-scale object recognition, with a measured 94% accuracy for a face detection use-case.

SCIENTIFIC COLLABORATIONS: [1]STMicroelectronics, Grenoble, France

Context and Challenges

Preserving a well optimized 4T pixel while limiting ADC footprint and avoiding on-chip static power consumption were the three main design constraints for this wake-up imager. To achieve this while minimizing the dynamic power consumption, a scalable readout scheme has been developed, providing a thermometric-like bitstream format to lower complexity of digital pipeline operators. A 3-level awakening strategy implements 4b/6b motion detection and 6b object recognition. Fig. 1 reports its architecture including functional blocks.
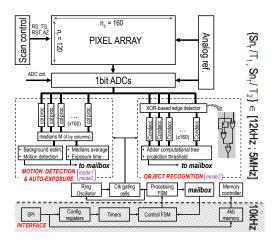

Fig. 1: Top-level wake-up CIS architecture.

Main Results

The column processors perform median-based background estimation and motion detection using a Δ modulation scheme. An edge-detection filtering compliant with the sequential bitstream provided by the *Fastscan* readout is performed, followed by a linear projection, without any frame memory, thanks to in-line conditional accumulators and a tree adder. Auto-exposure feedback control acts on a tunable ring-oscillator delivering the master clock that schedules *Fastscan* readout and processing. This always-on image sensor has been fabricated using a 90nm 1P4M CIS process. The sensor's recognition capability and power consumption are reported on Fig. 2, outperforming the characteristics of prior works thanks to a unique low power combination of key features.
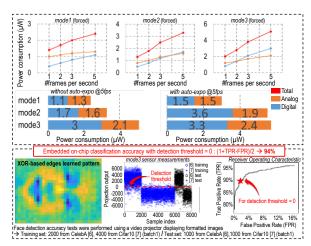

Fig. 2: Power measurements and inference performance.

Perspectives

Porting this design to a 3D-stacked technology will further decrease the power consumption and reduce the silicon footprint.

RELATED PUBLICATIONS:
[1] A. Verdant, W. Guicquero, N. Royer, G. Moritz, S. Martin, F. Lepin, S. Choisnet, F. Guellec, B. Deschamps, S. Clerc, J. Chossat, "A 3.0µW@5fps QQVGA self-controlled wake-up imager with on-chip motion detection, auto-exposure and object recognition", Symposia on VLSI Technology and Circuits (VLSI), June 14-19, Hawai, 2020

O4

X-RAY AND GAMMA IMAGING

- **Perovskite matrices detect X-rays and resolve them spectrally**

- **Compact in-line diffraction system detects counterfeit pharmaceuticals without opening their packaging**

- **To be more sensitive, coded-aperture CdZnTe Gamma imagers can be made thicker without losing their resolution**

Perovskites for spectral X-ray Imaging

RESEARCH TOPIC:

X-ray detectors, medical imaging, perovskites, spectrometry.

AUTHORS:

E. Gros-DAillon, O. Baussens, M. Chapran, A. Ibanez[2], J. Zaccaro[2], P. Rohr[3], J.-M. Verilhac[1]

CEA has been working for many years on medical imaging technologies. In this context, a new perovskite semiconductor material has been studied for spectral X-ray imaging. A process was developed to grow CH3NH3PbBr3 single crystals in solution. Small detector prototypes have been made with these crystals and evaluated in gamma-ray spectrometry. The first results show that it is possible to detect thus count individual gamma photons. However, the photoelectric peaks centred on the energy of the absorbed photons cannot be resolved at this stage. Key areas for improvement have been identified and developments are underway to optimise performance.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CEA, LITEN, F38000 Grenoble, France, [2] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, BP166, 38042 Grenoble, France, [3] Trixell, 38430 Moirans, France

Context and Challenges

Improvements in medical X-ray imaging contribute to improve the diagnosis and treatment of many diseases. The next breakthrough in X-ray imaging may be high spatial resolution X-ray spectral imaging which will enable to achieve metabolic contrast. Halogenated perovskites semiconductors are promising candidates for such detectors. The objective of this study was to demonstrate the proof of concept of gamma detection on a small prototype.

Main Results

Single crystals of $CH_3NH_3PbBr_3$ were grown in solution as a model material. A full-field electrode that blocks holes injection was evaporated on one side of the crystal to decrease dark current. An array of metallic electrodes with a 600µm pitch was evaporated on the other side of the crystal. These detectors were hybridised on a printed circuit board (fig. 1).

Bumps on a printed circuit board

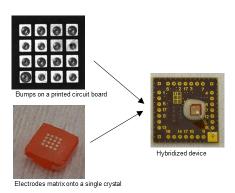Hybridized device

Electrodes matrix onto a single crystal

Fig.1: Hybridization on a reading circuit

Finally, these devices were tested under gamma irradiation to evaluate the energy discrimination of the device. Gamma photon counting was demonstrated for the first time with this composition, but the photoelectric peaks are not yet visible (fig. 2).
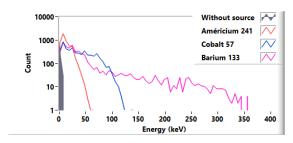

Fig.2: Gamma spectra acquired using a hybrid device

Perspectives

The key issues to be addressed in order to improve performance were identified. In particular, the electronic noise must be reduced, the mobility of the charge carriers increased and the integration process on a readout matrix must be adapted to a large area (40×40cm²).

RELATED PUBLICATIONS:

[1] An insight into the charge carriers transport properties and electric field distribution of CH3NH3PbBr3 thick single crystals, O. Baussens, L. Maturana, S. Amari, J. Zaccaro, JM. Verilhac, L. Hirsch, E. Gros-Daillon, Appl. Phys. Lett. 117, 041904 (2020)

[2] Optimization of the growth conditions for high quality CH3NH3PbBr3 hybrid perovskite single crystals, S. Amari, J. M. Verilhac, E. Gros D'Aillon, A. Ibanez, et J. Zaccaro, Cryst. Growth Des. 2020, 20, 3, 1665–1672

A compact, in-line diffraction system to detect counterfeit pharmaceuticals in their packaging

RESEARCH TOPIC:
X-ray diffraction, counterfeit medicines, control of medicine packages, CdZnTe spectrometric detectors, collimation

AUTHORS:
J. Tabary, M-C. Gentet, O. Monnet, C. Greffe[1], D. Koch[1], N. Tallet[2]

Medicine counterfeiting is a health and economic problem that the pharmaceutical field has to deal with. X-ray diffraction, known to be very specific in characterizing the structure of molecules, can be an interesting technique for detecting counterfeit drugs without having to take them out of their packaging.

In this context, we have developed a relatively compact system which combines the use of an integrated X-ray source and a compact high-performance CdZnTe imager. This system has been tested on several drugs and has shown its ability to easily detect counterfeit pharmaceuticals in their packaging in less than a few minutes.

SCIENTIFIC COLLABORATIONS: [1] X-RIS SRL, Herstal, Belgique, [2] SANOFI LCAC, Tours, France

Context and Challenges

The DIFCOM project aimed to offer a new technological solution to fight against medicine counterfeiting, which constitutes an increasing health and economic problem. The purpose was more precisely to use the energy dispersive x-ray diffraction technique to detect counterfeit drugs on site, in real time and in their containers (blisters, boxes, postal parcels).
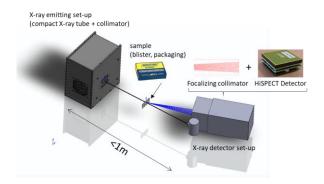
Main Results

A control system prototype was therefore dimensioned and implemented experimentally at CEA. It measures around one meter long, and combines a compact conventional x-ray tube, used at 80kV, and a compact 2D spectrometric CdZnTe based imager (called HiSPECT) developed in our lab. A focalizing collimation has been specifically designed to detect only the photons that scatter inside the package towards the entire surface of the imager.
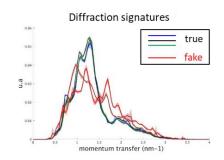
This system was tested on several drugs supplied by SANOFI, each time with authentic and counterfeit samples. Even with x-ray sources operating at only 80 W, detection of counterfeits has been found to be possible in a time ranging from seconds to minutes, depending on the type of drug.

Perspectives

These promising results opens the door to fast wearable equipment (<25kg) able to easily detect counterfeit pharmaceuticals without damaging their packaging. Such a system could be used as a second level, at the end of an already existing parcel control system. Another perspective could be to decline this system to a portable system for detecting improvised explosive device in abandoned packages. Project ANR-17-CE39-0017 was funded by ANR (French National Research Agency)

Sketch of the final DIFCOM control system

Measured diffraction signatures of true/fake drugs

RELATED PUBLICATIONS:
[1] G. Montémont, et al. "Recent Improvements to HiSPECT Imaging Module". IEEE Nuclear Science Symposium (NSS/MIC'16), Oct 2016, Strasbourg, France

Impact of detector thickness on performance of NuVision Gamma imager

RESEARCH TOPIC:
X and gamma-ray imaging

AUTHORS:
G. Montémont, B. Feret [1], O. Monnet, D. Rothan [1], S Stanchina, L. Verger

The NuVISION coded-aperture/Compton portable gamma-ray imager is based on CdZnTe detectors enabling sub-pixel resolved 3D positioning. This system is based on nuclear medicine 40×40 mm modules with 2.46 mm anode pitch for a total of 256 readout channels. 5 and 6 mm thick crystal are widely available. However, performance for energies above 200 keV is undermined by the poor efficiency of these detectors to high energy photons. For radiation safety and security applications, it is then relevant to use thicker detectors. In this paper, we evaluate the use of 10 mm thick detectors by both simulation and experimentation, for application in coded aperture imaging and Compton imaging.

SCIENTIFIC COLLABORATIONS: [1] Nuvia France

Context and Challenges

NuVision is a CdZnTe-based detector plane of 40×40 mm area. Signals of anodes are analyzed by digital electronics (FPGA) in order to locate interactions in 3D inside the detector. We have compared 6mm-thick standard detector to 10mm -thick high efficiency detector, that offers better efficiency (16 cm³ volume) and better spectrometric capability.
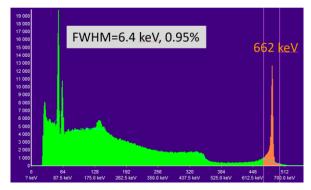We used jointly two imaging techniques: Compton and code-aperture imaging.

Main Results

First, we have shown that there was no negative impact of thickness on spatial resolution. Moreover, it improves in average inside detector volume.
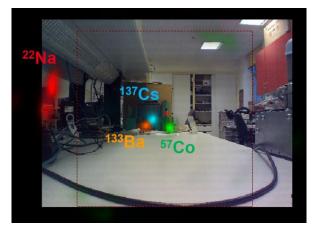With thick detectors, isotope identification is faster for two reasons: higher efficiency and better peak-over-Compton ratio (7 instead of 3). Photoelectric peak is then 3× more intense at 662keV. Coded aperture imaging is 2× faster at 662keV with the same angular resolution (2.3°). Compton Imaging is 3× faster at 662keV and less sensitive to artefacts.
To conclude, using thicker detectors has very positive effects on performance that balance the slightly higher cost of the crystal.

Perspectives

To enhance further imaging sensitivity and field of view, we will study impact of the geometrical arrangement of multiple detectors in combination of mask design.
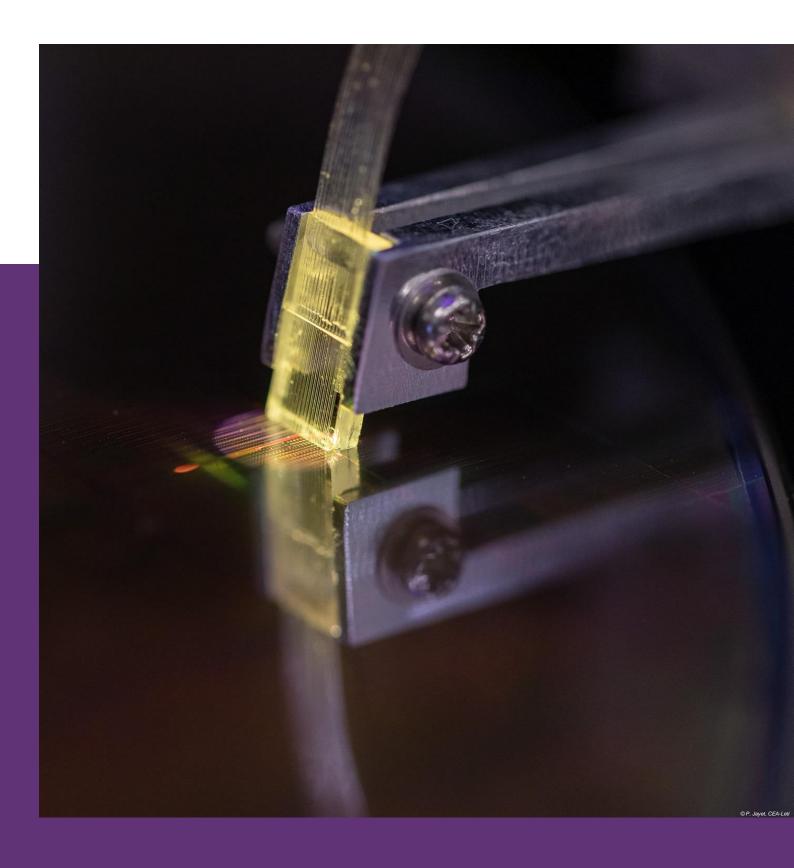

Spectrum with a 10mm thick imager

Multi-isotope image with 10mm imager.

RELATED PUBLICATIONS:
[1] G. Montémont et al., IEEE Transaction on Nuclear Science, vol. 61, no. 5, pp. 2559--2566, Oct. 2014.
[2] G. Montémont et al., IEEE Nuclear Science Symposium and Medical Imaging Conference, 2017.
[3] G. Montémont et al., IEEE Nuclear Science Symposium and Medical Imaging Conference, 2020.

O5

SILICON PHOTONICS

- **Non-conventional integrated nanophotonic devices are designed by pixel-by-pixel optimization**

- **III-V bonding on Si followed by III-V epitaxy results in efficient multi-wavelength lasers**

- **NbN superconductor integrated with Si photonics detects single photons**

Integrated nanophotonic devices demonstration based on pseudo-graded index and pixel-by-pixel opimizations

RESEARCH TOPIC:

Silicon photonics, numerical opimizations, nanophotonics, graded index

AUTHORS:

K. Hassan, S. Boutami, J.-A. Dalley[1], P. Bricanceau (Leti/DPFT), C. Dupré, M. M. R. Elsaway[2], L. Baud, S. Lanteri[2], and S. Fan[3]

Nanophotonic devices can be designed by a large set of analytical and numerical tools (parametrized computation, transformed-optics, metamodeling, inverse design…), with an increasing number of experimental demonstrations in the past decade, thanks to progress in nanofabrication applied to integrated optics, and especially silicon photonics. In this work, we report on two type of devices, with first a nanophotonic metalens based on pseudo-graded index binary shaping through analytic and Bayesian optimization, and second a nanobend designed through adjoint variable method-based deterministic optimization. These devices allows us to highlight various challenges in term of numerical optimization and nano-manufacturing exhibiting minimum feature size below 100nm.

SCIENTIFIC COLLABORATIONS: [1]Vistec Electron Beam GmbH, Jena 07743, Germany. [2]Univ. Côte d'Azur, Inria CNRS, LJAD, 06902 Sophia Antipolis, France. [3]Dept. of Electrical Engineering, Stanford University, Stanford, California 94305, USA
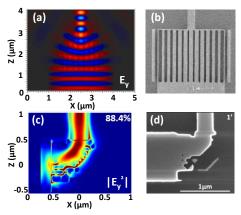
Context and Challenges

The development of nanophotonic components rely on innovative modeling and state-of-the-art manufacturing processes. The design of ultra-compact devices requires advanced computational methods such as transformation optics (TO) or inverse design in order to obtain the desired function exhibiting non-intuitive shapes and featuring subwavelength elements. These methods can be opposed to traditional parametric optimizations for which a large number of degrees of freedom would be necessary to reach the same results. Here we report on the realization of two set of devices, a metalens based on pseudo-graded index medium and a nanobend designed through adjoint variable method (AVM) with a deterministic binary optimization.

Main Results

First part of this work demonstrates an integrated metalens enabling mode conversion between the fundamental mode of a multimode waveguide and that of a single-mode waveguide (Figure 1 (a, b).) The device was fabricated using industrial tools on large-scale wafers, by mean of e-beam lithography (VISTEC VB6B). We have shown that for such pseudo-graded index devices 2nd-order effective medium theory (EMT) can be inaccurate in generating the correct effective index profile while FEM mode calculation provides an accurate model, making design uncertainty negligible compared to the experimentally observed fabrication variations [1]. The proposed design approach is exclusively 2D, requiring low computational resources, although efficient global optimization (EGO) implementation with Discontinuous Galerkin Time-Domain (DGTD) solver shows a benefit to optimize such a device in the TE case [2].

In a second part of this work, we have demonstrated silicon photonic devices obtained by a discrete pixel-by-pixel optimization approach (Figure 1 (b, c)), which guarantees a binary optimized structure thanks to a Green's function formalism [3]. This approach probes a large phase space in each iteration, with a straightforward handling of technological constraints imposed by lithography. The experimental results, comparing both e-beam and deep-UV immersion lithography, confirm the advantage of this approach as compared with an approach based on traditional AVM.

3D-FDTD models and SEM images of a (a, b) nanophotonic metalens [1] and (b,c) nanobend [2]

Perspectives

In summary, we have shown that simplified analytic formalism together with 2D calculations provides a reliable framework for the design of pseudo-graded index nanophotonic devices, which could certainly help wide spreading of TO-based integrated circuits. Advanced computational methods allows going deeper towards high performances, either with the EGO-3D-DGTD for the first case, or through the deterministic pixel-by-pixel optimization shown for the second case. The later approach may be particularly useful in circuits fabricated by optical immersion lithography, since it can directly take into account the minimum feature size requirement in the lithographic approach.

RELATED PUBLICATIONS:

[1] K. Hassan et al., Integrated photonic guided metalens based on a pseudo-graded index distribution. Sci Rep **10**, 1123 (2020). https://doi.org/10.1038/s41598-020-58029-z

[2] M. M. R. Elsaway et al., Bayesian optimization and rigorous modelling of a highly efficient 3D metamaterial mode converter. OSA Continuum 3(6), 1721 (2020). https://doi.org/10.1364/OSAC.393220

[3] S. Boutami et al., Experimental demonstration of silicon photonic devices optimized by a flexible and deterministic pixel-by-pixel technique. Appl. Phys. Lett. **117**, 071104 (2020). https://doi.org/10.1063/5.0013558

New opportunities in III-V-on-Si integration for higher capacity optical networks: epitaxy on InP bonded on Si

RESEARCH TOPIC:
Integration of IIIV on Si is facilitated by bonding IIIV on Si, new developments enable the epitaxy on a bonded InP layer on Si

AUTHORS:
C. Dupré, C. Besançon[1], F. Fournel (Leti/DPFT), V. Muffato, L. Sanchez, D. Néel[1], D. Make[1], F. Pommereau[1], J. Decobert[1], C. Jany (Leti/DPFT), T. Baron[2], F. Bassani[2]

Direct bonding of IIIV on Si offers the possibility of a high crystalline quality of IIIV on Si. Recent work lead to enable the epitaxy once the InP layer is bonded on the Si wafer and InPoSi lasers were fabricated. The lasers performances obtained on InPoSi are similar to the reference, validating the newly developed building block. It can be applied in various cases, for instance Selective Area Growth (SAG) which allows obtaining a wide range of emission wavelengths with a single epitaxial growth onto a wafer. SAG process has been performed on InP bonded on a Si, creating a multi-λ laser array onto silicon based on a single growth step covering a 155 nm-wide range.

SCIENTIFIC COLLABORATIONS: [1] III-V Lab, a joint lab of Nokia Bell Labs, Thales Research and Technology and CEA LETI, 91120 Palaiseau, France, [2] Univ. Grenoble Alpes, CNRS, CEA LETI Minatec, LTM, F-38054 Grenoble Cedex, France

Context and Challenges

The increasing demand in datacenter for higher capacity networks pushes a step forward the integration of InP-based Photonic Integrated Circuits (PICs). The Si CMOS platform offers low cost and large-scale manufacturing of various optical functions. However, the integration of III-V semiconductors onto Si wafers is mandatory to fabricate efficient light sources. Direct IIIV growth on Silicon offers the most promising approach to enable light generation on Si substrate at low cost, but remains difficult due to lattice mismatch between InP and Si.

Main Results

Direct bonding of InP on Si offers the possibility of a high crystalline quality. Recent work lead to enable the epitaxy once the InP layer is bonded on the Si wafer. Figure 1 demonstrates the successful MQW-based laser structure regrowth on InP bonded on Si (InP-SiO2/Si = InPoSi). The InPoSi laser performances are similar to a reference laser fabricated on InP substrate (Figure 1c), validating the new building block. It can be applied in various configurations. For instance, Selective Area Growth (SAG) allows obtaining a wide range of emission wavelengths with a single epitaxial growth onto a wafer. The growth rate of multiple quantum wells (MQW) is locally enhanced thanks to the pattern of SiO2 mask defined prior to the epitaxy step (Figure 2). As a result, the MQW bandgap is tuned. SAG process has been performed on InP bonded on a Si, creating a multi-λ laser array onto silicon based on a single growth step (155nm range).
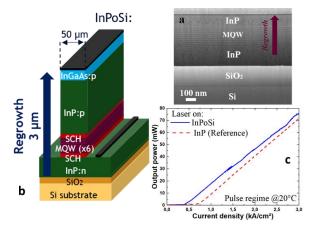

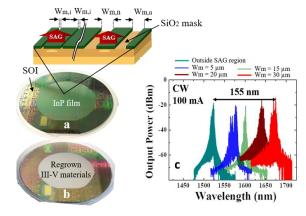**Fig. 1: InPoSi regrown laser & J-L characteristics**

Fig. 2: SAG applied to create multi-λ laser array

RELATED PUBLICATIONS:
[1] C. Besancon et al., IEEE PTL vol. 32, n°8, 2020, https://doi.org/10.1109/LPT.2020.2979254
[1] C. Besancon et al., ECOC, 2020, https://doi.org/10.1109/ECOC48923.2020.9333230

Optimized niobium nitride superconducting thin film for high-efficiency waveguide-integrated single photon detectors

AUTHORS:
S. Olivier, R. Rhazi, Y. Désières, G. Rodriguez (Leti/DPFT), E. Monroy[1], C. Bougerol[1], S. Lequien[1], J.-L. Tomassin[1], J.M. Gérard[1]

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 a high-quality NbN superconducting material with optimized critical temperature compatible with close to 4K operation and suitable for single photon detection. This demonstration is a first step towards a fully integrated quantum photonics platform including single photon sources, coherent manipulation circuits and superconducting nanowire single photon detectors.

SCIENTIFIC COLLABORATIONS: [1]CEA-IRIG

Context and Challenges

Single photons, which are fast and feature excellent robustness against decoherence effects, are ideal qubits for emerging applications such as perfectly secure quantum communications and quantum computing. Such 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, coherent manipulation and detection on-chip. In this report, we focus on the development of a high-quality material for waveguide-integrated superconducting nanowire single photon detectors (SNSPDs).

Main Results

We have selected niobium nitride material (NbN), as it features the highest critical temperature, around 5K for a thin NbN film of 5 nm directly deposited on Si.
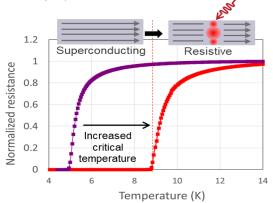

Fig. 1 : Evolution of the resistance of a thin NbN film of 5 nm as a function of temperature with (red) and without (purple) a thin AlN buffer layer Ou Fig. 1 : Superconducting behaviour

Thanks to the introduction of a thin AlN buffer layer of 10 nm prior to NbN deposition, we have improved the cristalline quality of NbN, leading to an increase of its critical temperature up to 8.5K (Fig. 1), compatible with SNSPD operation close to 4K. This AlN/NbN stack was patterned into a nanowire and embedded in a simple fiber-coupled vertical cavity architecture to validate the ability of the material to detect single photons (Fig. 2).
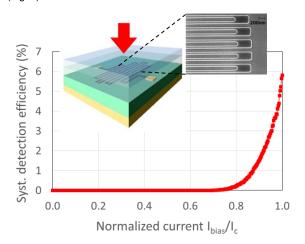

Fig. 2 : Detection efficiency of an AlN/NbN nanowire embedded in a simple fiber-coupled vertical SNSPD architecture Ou Fig. 2 : Single photon detection with AlN/NbN material

Perspectives

This demonstration is a first step towards the development of waveguide-integrated SNSPDs exhibiting high efficiency and low dark counts, suitable for advanced quantum communication protocols and quantum computing processors.

RELATED PUBLICATIONS:
[1] R. Rhazi et al., "Improvement of critical temperature of niobium nitride deposited on 8-inch silicon wafers thanks to an AlN buffer layer", Superconductor Science and Technology 045002 (2021)

O6

OPTICAL ENVIRONMENTAL SENSORS

- **Cavity optomechanics detects trace gases**
- **Optical transduction of mechanic vibrations improves photo-acoustic and photo-thermal detection of trace gases**
- **GeSn LEDs allow detecting methane in air**
- **Mid-infrared multispectral imaging identifies cancerous tissues**

Cavity optomechanics for trace-gas detection

RESEARCH TOPIC:
Cavity optomechanics, Trace gas spectroscopy, Near-Infrared (NIR) fiber-based optomechanics, Mid-Infrared (MIR) optomechanics

AUTHORS:
Joris Baraillon, Pierre Labeye, Laurent Duraffourg (Leti/DCOS)

CEA-Leti is involved on research on cavity optomechanics, which explores the mutual interaction of electromagnetic radiation and mechanical vibrations. In most optomechanical systems, the radiation pressure force is amplified by an optical cavity of high finesse. Under certain conditions, this optical force induces several phenomena on the mechanical dynamics, and is responsible for a strong dependency of the mechanical properties on the optical losses. Consequently, among other optomechanical sensors, trace-gas spectroscopy with optomechanical transduction is considered. This involves proof of concept with NIR fiber-based setups with commercial optical and mechanical elements, and the first realization of MIR silicon integrated optomechanical cavities.
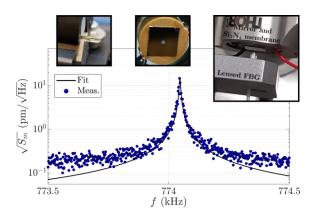
Context and Challenges

Gas detectors are commonly used in many applications for instance in industrial safety, environmental analysis for greenhouse gases detection or health-care for breath-gas monitoring. One of the most common techniques is usually based on a direct measurement of the optical absorption in the MIR region.
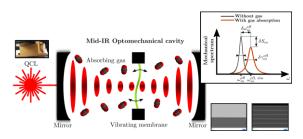
Main Results

Our work consists in developing a new concept of all-optical gas sensor with an optomechanical transduction, based on a mechanical membrane in a middle of a high finesse Fabry-Perot cavity, designed near an absorption wavelength of the gas of interest. The optomechanical interaction modifies the mechanical properties of the membrane, in particular through the optical spring effect. This shift of the mechanical resonance frequency induced by the radiation pressure force is strongly dependent on the optical losses. Consequently, by modulating the laser frequency around the absorption wavelength, we modulate the intrinsic optical losses and therefore the resonance frequency of the membrane. Quantifying this variation by means of an optical readout of the mechanical motion allows us to measure the gas concentration.

Perspectives

Measurements of thermomechanical spectrum of silicon nitride membrane have been performed with NIR fiber-based proof-of-concept using lensed Fiber Bragg Grating (FBG) and dielectric mirrors in vacuum environment. The first silicon integrated MIR optomechanical cavities using Bragg multilayer mirrors are currently in fabrication at the CEA-Leti cleanroom platform.

Thermomechanical spectrum with NIR fiber-based optomechanical cavities

MIR optomechanical cavity for trace-gas detection

RELATED PUBLICATIONS:
[1] J. Baraillon *et al.*, "Cavity optomechanics for trace gas detection", Proc. SPIE 11697, MOEMS and Miniaturized Systems XX, 116971 (Oral)
[2] J. Baraillon *et al.*, "Linear analytical approach to dispersive, external dissipative, and intrinsic dissipative couplings in optomechanical systems", Phys. Rev. A 102, 033509

Optical transduction for photoacoustic and photothermal detection of trace gas using Fabry – Perot resonators

RESEARCH TOPIC:
Resonant optical cavity, Fabry – Perot, Photoacoustic, Photothermal, Trace gas detection

AUTHORS:
T. Lauwers, A. Glière, S. Basrour[1], T. Verdot (LETI/DCOS), G. Laffont[2], R. Cotillard[2]

We have evaluated the interest of optical resonant transducers based on the Fabry – Perot cavity for trace gas detection. Two approaches have been studied with the help of comprehensive multiphysics lumped elements models. The systems were fabricated, characterized, and implemented in gas sensors. In a first approach, a low finesse Fabry – Perot cavity, placed at the tip of an optical fiber, allowed to reach state of the art limit of detection for photoacoustic sensors. In the second one, based on an original principle, the resonant cavity is limited by two Bragg mirrors, laser written inside the core of an optical fiber. This prototype takes advantage of the cavity resonance shift due to the photothermal effect occuring in the gas surrounding the optical fiber.

SCIENTIFIC COLLABORATIONS: [1] Université Grenoble Alpes, CNRS, Grenoble INP, TIMA, [2] Université Paris Saclay, CEA, LIST

Context and Challenges

Most often, the pressure sensor used in photoacoustic detectors is either a MEMS microphone or a mechanical quartz resonator. Optical transduction represents a promising alternative, allowing in particular remote and ignition free sensing for operation in harsh or hazardous environments. In this work, we focus on Fabry – Perot cavities, where the slight shift of the optical cavity resonance, induced by acoustic or thermal perturbations, can be detected.

Main Results

We have designed, fabricated and tested a transducer based on a low finesse Fabry – Perot cavity, assembled at the tip of an optical fiber, and a cheap laser diode [1,2]. The first mirror of the cavity is constituted by the tip of the cleaved fiber, while the second one is formed by a mechanically resonant cantilever beam, adapted to the measurement of weak acoustic signals by the addition of a hinge on the clamped side of the cantilever. The sensor has been designed thanks to a complete lumped element model, devised to predict the coupled multiphysics behavior of the mechanical structure, the surrounding gas, and the excitation light source. As can be seen on the figure, the model (solid lines) fits accurately with experimental results (dots) obtained for various hinge lengths. The limit of detection at the resonance frequency of the optical microphone is close to 2 µPa/√Hz. The acoustic transducer has been integrated in a photoacoustic sensor and calibrated with several mixtures of nitric oxide in nitrogen. The detection limit is estimated to be around 10 ppb [2].
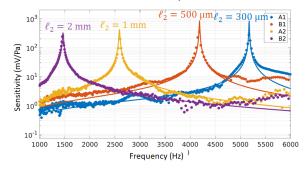
Perspectives

With the help of silicon MEMS microfabrication techniques, the foreseen miniaturization of the prototype sensor would bring several benefits such as e.g. better manufacturing tolerances and reduction of the ventilation slit surrounding the hinged cantilever. Besides, once the transducer dimension will be reduced to that of the fiber ferrule, it will become possible to take full advantage of the favorable downscaling behavior of the photoacoustic effect.

In addition, a second and original approach, consisting of a phase shifted Fabry – Perot cavity fabricated on an optical fiber has been investigated [3]. Here, the cavity is delimited by two Bragg mirrors - periodic spatial variation of the refractive index - laser written in the optical fiber core. Unlike in the previous solution, (i) a very high finesse cavity is achieved, (ii) a sophisticated Pound – Drever – Hall optical locking technique, extremely sensitive to optical resonance shifts is harnessed and (iii) short range photothermal perturbations are exploited. The limit of detection, barely estimated on atmospheric CO_2 measurements, is in the order of one ppm. This proof of concept is quite promising as much room is left for technical improvement and as a real potential exists for implementation in planar photonic integrated circuits.

Acoustic response for several hinge lengths

RELATED PUBLICATIONS:
[1] T. Lauwers, A. Glière, and S. Basrour, "An all-Optical Photoacoustic Sensor for the Detection of Trace Gas," Sensors, vol. 20, no. 14, 2020, doi: 10.3390/s20143967.
[2] T. Lauwers, A. Glière, and S. Basrour, "Resonant optical transduction for photoacoustic detection," presented at Photonics West, San Francisco, USA, Feb. 01-06, 2020. Available: https://hal-cea.archives-ouvertes.fr/cea-02481249.
[3] T. Lauwers, "Optical transduction methods for the photoacoustic and photothermal detection of trace gas", PhD, Univ. Grenoble Alpes, 2021

Group-IV heterostructures LEDs for gas detection

AUTHORS:

L. Casiez, M. Bertrand, N. Pauc[1], J. Chretien[1], A. Quintero (LETI/DPFT), Q. M. Thai[1], M. Frauenrath (LETI/DPFT), O. Lartigue, P. Barritault, N. Bernier (LETI/DPFT), P. Rodriguez (LETI/DPFT), V. Calvo[1], J.-M. Hartmann (LETI/DPFT), A. Chelnokov, V. Reboud

Direct-band gap GeSn alloys have strong potentials as MIR light emitters. We investigated LEDs with 16% of tin. Light emission was observed up to room temperature and the $Ge_{0.84}Sn_{0.16}$ LED was used in a gas sensor to detect CH_4.

SCIENTIFIC COLLABORATIONS: [1] Univ. Grenoble Alpes, CEA, IRIG-DePhy, 38054 Grenoble, France.

Context and Challenges

Silicon photonics in the near-Infra-Red, up to 1.6 µm, is already one of key technologies in optical data communications, particularly short-range. However, silicon photonics does not yet cover a large portion of applications in the mid-IR. In the 2 to 5 µm wavelength range, environmental sensing, life sensing, and security all rely on optical signatures of molecular vibrations to identify complex individual chemical species. The markets for such analysis are huge and constantly growing, with a push for sensitivity, specificity, compactness, low-power operation and low cost. An all-group-IV, CMOS-compatible mid-IR integrated photonic platform would be a key enabler in this wavelength range. Ge can be turned into a direct bandgap semiconductor by alloying with more than 8% of Sn, typically. We succeeded to fabricate light emitting devices (LEDs) from thick GeSn layers epitaxied on Ge Strain-Relaxed Buffer (SRBs). Light emission was obtained up to room temperature for $Ge_{0.84}Sn_{0.16}$ LEDs. Those LEDs were used in a gas sensor cell to detect CH_4.

Main Results

The growth of GeSn alloys was performed by Reduced-Pressure Chemical Vapor Deposition (RP-CVD) on p-type doped Ge SRBs on 200 mm Si (001) wafer at CEA-LETI. Circular mesa-like LEDS were then fabricated [1]. A NiPt alloy was deposited then capped with TiN. After a Rapid Thermal Annealing below 350°C, an intermetallic nickel stanogermanide phase was formed with the Ge injection layer. Finally, 20 nm of Ti and 180 nm of Au were deposited by evaporation on the NiPt/TiN contacts [2]. LEDs with a GeSn 16% active layer were used in an absorption gas cell to detect CH_4 gas. The fluctuation of the light source signal is measured by a thermopile at the other end of the tube filled with different concentration of CH_4. The acquired signal from the thermopile is proportional to the transmitted signal at different concentrations of CH_4 in the tube (Figure 1c).
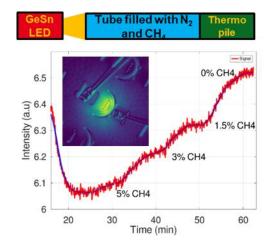

Fig. 1: Schematics of the gas sensor cell and light variation from $Ge_{0.84}Sn_{0.16}$ LED absorbed by different concentrations of CH_4 in the gas sensor cell tube, Inset: Thermal imaging of fabricated a $Ge_{0.84}Sn_{0.16}$ LED emitting at room temperature,

Perspectives

Our preliminary and very simple gas-sensing set-up has a great margin of improvement in terms of drift and gas circulation. Our results nevertheless show that GeSn alloys are promising light sources for gas sensing. Investigations are underway to further increase light extraction from LEDs and improve their performances.

RELATED PUBLICATIONS:

[1] L. Casiez *et al.*, GeSn heterostructures LEDs for gas detection, IEEE Photonics Conference (IPC), Vancouver, BC, Canada, 1-2, (2020) doi: 10.1109/IPC47351.2020.9252514.

[2] A. Quintero *et al.*, Impact of alloying elements (Co, Pt) on nickel stanogermanide formation, Mater. Sci. Semicond. Process., 108, 104890 (2020).

MID-infrared multispectral imaging for cancer tissue detection

RESEARCH TOPIC:
Infrared spectroscopy, lensless imaging, infrared instrumentation, cancer diagnosis, multivariate statistics, machine learning

AUTHORS:
G Mathieu, S Bonnet (LETI/DTBS), V Rebuffel (LETI/DTBS), J-L Coll[1], M Henry[1], M Dupoy

As the number of cancers is steadily increasing, doctors are in need of automatic tools with better and faster analysis methods to help them with the diagnosis. One way to tackle this challenge is to propose label-free methods capable to analyze a large number of samples. Mid-IR imaging can provide an unequivocal information about the biochemical composition of human cells. We develop a new IR optical imaging platform with several innovative LETI/DOPT photonics components such as quantum cascade laser (QCL), photonics integrated circuits and uncooled bolometer array. This experimental setup coupled to machine learning algorithms can help to classify the biological cells in a fast and reproducible way. We achieved encouraging results on cancer cells classification

SCIENTIFIC COLLABORATIONS: [1]IAB, Univ. Grenoble Alpes, F-38000 Grenoble

Context and Challenges

The standard histopathological diagnosis assessments remain subjective and therefore poorly reproducible among pathologists. We propose to improve this method by aiding objective information about biochemical composition of the tissues in the form of Mid-IR multispectral images. The combination of a set of six QCLs with an uncooled LETI bolometer matrix will allow the biochemical mapping over a wide field of view by the lensless imaging principle. This experimental setup coupled to machine learning algorithms enable very fast biochemical cartographies on tissue.

Main Results

Six images were acquired by placing the frozen section tissue of nude mice bearing human oral cavity tumors a few millimeters away from microbolometer and lightening them successively with 6 different QCLs, at wavelengths corresponding to the DNA and protein absorption bands. The images shown in Fig.1 are from a stitching of 28 fields contain simultaneously biochemical and morphological information building the univocal fingerprint of the samples. Preliminary supervised classification results (confusion matrix given in Fig. 2) are encouraging and demonstrate the system's ability to discriminate quite well between normal and cancer tissues.

Perspectives

Lensless multispectral mid-infrared imaging is a promising diagnosis technology based on transmission imaging of tissue section. The next challenge is to confirm these results on real human samples. This microscopy platform is efficient user friendly allowing its use in hospitals.
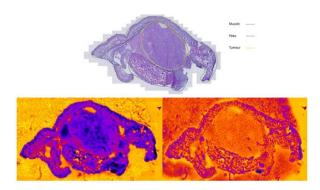

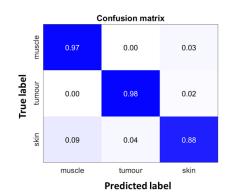**Fig. 3: Microscope image (visible) and two typical** transmission IR images

Fig. 4: Confusion matrix by the random forest algorithm.

RELATED PUBLICATIONS:
[1] G. Mathieu et al « Mid infrared multispectral imaging for tumorous tissue detection », in Imaging, Manipulation, and Analysis of Biomolecules, Cells, and Tissues XIX, Online Only, United States, march 2021, p. 5, doi: 10.1117/12.2577221.

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07 AR/VR MICRODISPLAYS

- **Highly transparent photopolymers are developed for near-eye holographic AR displays**

- **Holography imprints image-forming optical elements of near-eye AR displays**

- **Chiral polymer LEDs emit circularly polarized light**

- **Hybride quasi-2D perovskites act as efficient green LEDs**

- **GaN microLED displays call for an efficient surface passivation**

- **Novel model assesses reliability of microLEDs**

- **2D core-shell nano-platelets convert color in GaN microLED displays**

- **Bright GaN microLED displays call for specific CMOS driving circuits**

- **Large matrices of binary GaN microLEDs multiply bandwidth of Visible Light Communications.**

- **Fine pitch copper pillar integration enables microLED displays**

- **Curved microdisplays simplify AR/VR optical systems**

High transparency holographic photopolymer formulation for Augmented Reality applications

RESEARCH TOPIC:
Holography, photosensitive material, photopolymer, Augmented Reality, smart glass

AUTHORS:
Paul Legentil, Christophe Martinez, Marie-Claude Gentet, Yann Lee, Sylvia Meunier-Della-Gata, Cloé Bereziat

Augmented Reality (AR) has been attracting attention for several years. Now, the commercialisation of reliable devices is the next challenging step. Holography is one of the more relevant technology for this kind of device development as it allows controlling light properties while keeping the device transparency. CEA Leti is evaluating a device concept based on silicon photonics and holography and both the access and the knowledge on the holographic material is of primary importance. We describe our first result on the chemical formulation of high transparency holographic photo-polymers for AR applications. We demonstrate our ability in mastering different characteristics such as the thickness of the film, the refractive index modulation or the sensitivity.

Context and Challenges

The use of holography in optical devices is a tremendous challenge for the "DOPT" for several years [1]. The physic-chemical mechanisms understanding of the different holographic materials, their behaviours during holograms writing and their resulting properties would lead to a better mastery of their integration in optical systems.

Main Results

Commercial silver halide (SH) materials are currently studied in our laboratory and are very reactive materials which permit fast printing of well-defined holograms with high refractive index modulation Δn (Figure 1) [2]. However, SHs need a cumbersome wet-chemical processing after the interference exposure to develop holograms and present a low transparency. Simultaneously we are also working on Photo-Polymer (PP) materials. The physical-chemical mechanisms behind them are completely different (Figure 1). In addition to using a Covestro commercial PP [3], we have developed our own PP formulation ("CEA LETI PP") which exhibits suitable Δn for AR applications but foremost high transparency compared to other products. Figure 2 outlines both characteristics by presenting holograms recorded into CEA LETI PP, coated on a glass slide with a focus on the slide (left) and on the floor behind (right).

Perspectives

In addition to these very promising results, the strengthening of the photo-chemical phenomenon understanding as well as the enhancement of the material optical properties will open up a wide range of possible applications for our PP materials.
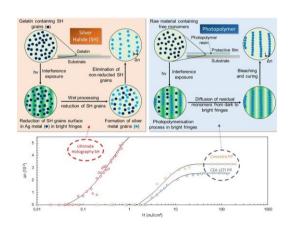

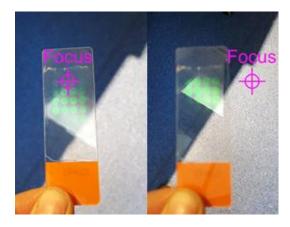**Fig.1: Evolution of Δn and writing mechanism illustration**

Fig.2: Holograms recorded into CEA LETI PP

RELATED PUBLICATIONS:
[1] Martinez, C., Krotov, V., Meynard, B. and Fowler, D., "See-through holographic retinal projection display concept," Optica 5(10), 1200–1209 (2018).
[2] Martinez, C., Gentet, M.C., Legentil, P., Lee, Y. and Colard, M., "Pixelated holographic reflector recording for retinal projection devices," Proc.SPIE, 117100L, doi.org/10.1117/12.2578221 (2021)
[3] Bruder, F.R., Frank, J., Hansen, S., Lorenz, A., Manecke, C., Meisenheimer, R., Mills, J., Pitzer, L., Pochorovski, I. and Rölle, T., "Expanding the property profile of Bayfol HX(R) film towards NIR recording and ultra-high index modulation," Proc. SPIE, 1171003, doi.org/10.1117/12.2578353 (2021)

Pixelated holographic reflector recording for retinal projection devices

RESEARCH TOPIC:
Holography, Augmented Reality, Photosensitivity, Smart Glass

AUTHORS:
C. Martinez, M.-C. Gentet, P. Legentil, Y. Lee, M. Colard

CEA-Leti is investigating an unconventional approach of smart glass design based on the recording of pixelated holograms. Due to the use on integrated photonics, this unconventional concept requires to adjust locally the properties of out-coupling holographic elements with specific angular distribution. As a first step for the development of the recording process we have studied a simple Lippmann recording configuration that focuses on the material behavior regarding the pixelated process. We demonstrate our ability to record distribution of holographic elements, few micrometers in size, and we use our experimental results to support first elements of simulation

Context and Challenges

Photonics industry has known tremendous progress in the past decades through the development of optical systems for Augmented, Virtual and Mixed Reality applications. Among the solution commercialized today a majority involves the use of a waveguide combiner that brings the image from the display engine to the eye through Total Internal Reflection [1]. Our laboratory has proposed to investigate another waveguide approach based on the use of single mode integrated photonics waveguides [2]. This unconventional solution requires the design and the manufacturing of holographic elements (hoels) densely distributed on the surface of the device, like pixels on a display. Each hoels distribution encodes a specific angular direction in order to form an Image directly on the retina.

Main Results

We have demonstrated in 2020 a first recording of a pixelated hologram in a simple Lippmann configuration, figure 1 [3]. This approach does not allows yet to encode angular direction but allows us to study the material behavior in the recording process. Uniform and well defined hoels have been recorded on a Covestro commercial Photo-Polymer (PP), figure 2. A close analysis of the hoel recording kinetics shows non homogeneous behavior that has still to be fully understood.

Perspectives

This first results pave the way to the demonstration of angularly defined hoels on a recording process currently under development in the laboratory with the use of an in house PP.
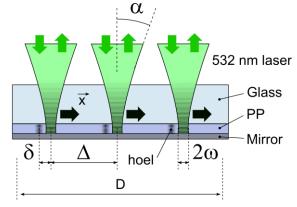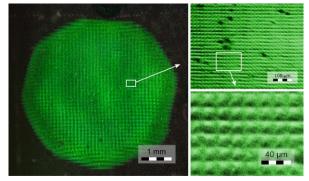

Fig. 1: Lippmann recording set-up

Fig .2: Macro and microscopic views of a pixelated hologram

RELATED PUBLICATIONS:
[1] Kress, B. C. and Chatterjee, I., "Waveguide combiners for mixed reality headsets: a nanophotonics design perspective," Nanophotonics, vol. 10, no. 1, pp. 41-74, (2021)
[2] Martinez, C., Krotov, V., Meynard, B. and Fowler, D., "See-through holographic retinal projection display concept," Optica 5(10), 1200–1209 (2018).
[3] Martinez, C., Gentet, M.C., Legentil, P., Lee, Y. and Colard, M., "Pixelated holographic reflector recording for retinal projection devices," Proc.SPIE, VL 117100L, doi.org/10.1117/12.2578221 (2021)

From organic material chirality to circularly polarized light: a new way of investigation for organic light emitting devices

RESEARCH TOPIC:
Display and Light source OLED based on Organic chiral molecule

AUTHORS:
B. Racine, E. Quesnel, G. Pieters[1] and L. Favereau[2]

So far, the property of chirality at the molecular level has been largely studied in particular in drug discovery and development, owing to its fundamental role in biological processes. However, more recently, this molecular dissymmetry, linked to the chiral molecule, has been extended to the research domain of organic materials, providing them with innovative properties such as a specific interaction with circularly polarized light. Given the potential of the latter in several research domains including display applications, cryptography, bio-imaging and spintronics, chiral molecular materials have been recently investigated at CEA-Leti to demonstrate the realization of innovative organic circularly polarized light emitting devices (CP-OLED).

SCIENTIFIC COLLABORATIONS: 1. DRF/JOLIOT/DMTS/SCBM/LMT CEA de Saclay, 2. Université de Rennes, CNRS, ISCR-UMR 6226

Context and Challenges

Organic light-emitting diodes (OLEDs) is one of the most promising technologies for display applications. However, specific issues regarding their practical use are still present as the luminescence efficiency lost due to the anti-glare filters in portable display devices. This issue can be avoided using a new generation of chiral organic molecule emitting light circularly polarized (CP) light.

Main Results

CPL emission is quantified with a dissymmetry factor, g_{lum}, which is related to IL and IR intensities of left and right CP emitted light. At molecular level the electronic transition from excited to ground state is influenced by the electric and magnetic transition dipole moment vectors and θ, the angle between them. In this case, glum is approximated as 4 |m| cos $(\theta)/(\mu)$ [1] where θ is controlled by the molecule chirality.

Chiral molecules based on a helicene were successfully synthetized by our partners. Depending on the substituent, they were found to exhibit various θ angles. The molecule with the lowest θ angle gave the highest g_{lum} (Fig.1). This molecule was, for the first time, successfully integrated into a top-emission OLED (Fig.2). This result highlights the potential of helical π-conjugated molecules for CP luminescence.

Perspectives

These new chiral materials can also induce spin selectivity. It could pave the way to organic materials with enhanced charge transport properties, which is today a strong limitation for organic material.
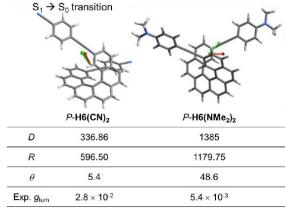

	P-H6(CN)$_2$	P-H6(NMe$_2$)$_2$
D	336.86	1385
R	596.50	1179.75
θ	5.4	48.6
Exp. g_{lum}	2.8×10^{-2}	5.4×10^{-3}

Fig. 1: S1→S0 transition vs substituent

Fig. 2: Realization of first CP-OLED

RELATED PUBLICATIONS:
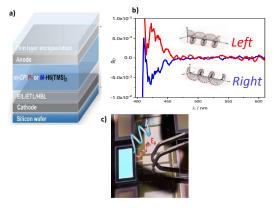[1] L. Frédéric et al., Adv.Funct. Mater., 2020, 30, 2004838.
[2] POLEM Project : https://www.cea.fr/presse/pages/actualites-communiques/ntic/oled-nouvelles-molecules.aspx and 18MP31 POLEM (cea.fr)
[3] K. Dhbaibi et al., Chem. Sci., 2021, DOI: 10.1039/D0SC06895K.

Hybride quasi-2D perovskites enable efficient green LEDs

RESEARCH TOPIC:
photonics, displays

AUTHORS:
S. Sandrez[1+Leti/DOPT], Z. Molenda1, L. Hirsch[1], G. Wantz[1], J.-P. Barnes (Leti/DPFT), C. Guyot (Leti/DPFT), O. Renault (Leti/DPFT), T. Maindron

Perovskite-LEDs (PeLEDs) are thin-film optoelectronic components that emit light when they are positively biased. Those studied in this work are based on the quasi-2D $PEA_2(FAPbBr_3)_{n-1}PbBr_4$ perovskite as emissive layer and organic semiconductors as charge transporting layers, as [ITO/PEDOT:PSS/poly-TPD/perovskite/TPBI/LiF/Al]. Integration of quasi 2D perovskite enables an efficient charge carrier confinement and high radiative recombination probabilities, leading to high emission efficiency, at least compared to 3D perovskites. Here, the optimization of the crystalline emissive layer, adjusting both composition and deposition conditions, allowed to build green PeLEDs with maximum current efficiencies of 43.6 cd/A (EQE, 9.6%).
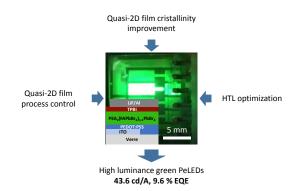
SCIENTIFIC COLLABORATIONS: Univ. Bordeaux, CNRS, Bordeaux INP, IMS, UMR 5218, F-33400, Talence, France

Context and Challenges

The perovskite-based light-emitting diode (PeLED) technology seems promising with conversion efficiencies already approaching those of more mature technologies (e.g. OLEDs) (Z. Wei et al., J. Phys. Chem. Lett., vol. 10, pp. 3035-3042, 2019).The work made between IMS and CEA-LETI aimed at identifying main hurdles for further development of efficient and stable PeLEDs.

Main Results

Research rapidly headed towards a structure with reduced dimension, the quasi-2D $PEA_2(FAPbBr_3)_{n-1}PbBr_4$ perovskite, enabling charge carrier confinement and radiative recombination probabilities improvement compared to 3D structures (L. Cheng et al., Adv. Mater., vol. 1904163, pp. 1–9, 2019). A strong focus has been made on the perovskite active layer optimization, adjusting both composition and deposition conditions, as well as on the Hole Transporting Layer (HTL), in a typical stack [ITO/PEDOT: PSS/HTL/perovskite/TPBI/LiF/Al]. Several parameters affecting the perovskite layer crystallization kinetics were identified. It was observed that the underlying layer for perovskite deposition has a strong impact on its crystallinity, implying distinct behaviors in appearance and evolution of quasi-2D phases with various dimensions. It was also shown that the anti-solvent process, consisting in perovskite crystallization acceleration by injecting a solvent during the spin-coating of the layer, is crucial in this quasi-2D system. An automated injection equipment was developed in order to help controlling this process and to study finely the anti-solvent addition time effect on layer morphology and resulting device performances. It revealed a narrow optimal process window leading to most efficient PeLEDs of around 0.5 s. In addition, the observation of a singular emission pattern on PEDOT: PSS/perovskite bilayer-based PeLEDs revealed a polymer electrical conductivity doping by the active perovskite layer. The conductivity substantially rose from 0.2 to 20 S/cm following the diffusion of some perovskite precursors into the PEDOT: PSS film. This diffusion was confirmed by ToF-SIMS analysis, with an estimation of precursors diffusion depth in the PEDOT: PSS in the order of 150 nm. This doping phenomenon was extended to several perovskites, deposited onto various PEDOT: PSS grades and other HTLs, like PTAA and poly-TPD. Implications on optoelectronic devices (PeLEDs and perovskite solar cells) of this unexpected doping process of HTLs during the spin-coating process of the quasi-2D perovskite film were assessed, unveiling a risk of overestimation of their performances (work recently submitted to Adv. Electron. Mater. [1]). Finally, the impact of HTL on PeLED devices was discussed. Depending on the HTL, reproducibility issues during perovskite layer deposition by spin-coating, due to wettability issues, as well as fluorescence dynamics fluctuation were observed. The integration of a poly-TPD layer finally enabled a substantial enhancement of PeLEDs performances, leading to a maximum efficiency of 43.6 cd/A (EQE 9.6%) for green PeLEDs.

Green PeLED showing high luminance (up to 30000 cd/m²
@ V < 6 V) and high efficiency (9.6 % EQE), after different
process optimizations (inset: typical PeLED architecture)

RELATED PUBLICATIONS:
[1] S. Sandrez et al., "Halide Perovskite Precursors Dope PEDOT:PSS," Adv. Electron. Mater., submitted, 2021

GAN based µLED passivation and cathodoluminescence characterization

RESEARCH TOPIC:
µLED, GaN passivation, Surface treatments, Atomic layer deposition, Al_2O_3 and cathodoluminescence characterization;

AUTHORS:
C. Le Maoult, D. Vaufrey

This work focused on GaN based LED and proposes a short characterization method to evaluate the suitability of various passivation process. Thanks to this approach implemented on LED stack mesa, surface treatments followed or not by dielectric deposition are investigated. Our studies underline that KOH treatment prior dielectric deposition help to passivate. As well, thermal atomic layer deposition of Al_2O_3, even at 250°C improve passivation.

Context and Challenges

We proposed a successfully attack scenario on SoC running an OS on a critical command, allowing Super User privilege escalation on Linux (su) [2]. This is the first study on a 64-bit chip with a complete software architecture, usable in a smartphone of its SoC. We focus on an A53-Cortex core, but it is a 64-bit multi-core SoC used in many smartphones, mainly at entry and mid-range price levels. A preliminary work has been performed on a test code in order to identify some required parameters for a successfully EMFI, such us the delay (figure 1) or to localize an EMFI-sensitive areas (figure 2).

Although the real scenario would require a synchronization tool, in addition to in uncontrolled environment, this approach can be used for forensic purposes to access protected or hidden data or to execute code.
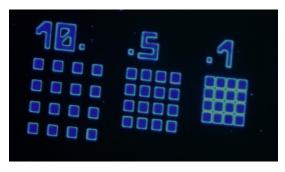

Fig. 1: photoluminescence image of GaN based stack LED mesas

Main Results

The characterization method consists in comparison of high resolution cathodoluminescence images performed on LED stack mesas implementing different surface treatments and/or dielectric deposition.[1,2] As was confirmed by time resolved measurements,[3] the slope of cathodoluminescence signal at the edge of the mesa is an indicator of the GaN passivation. As example, the Fig. 2 displays an example of cathodoluminescence spectrum cross section through a mesa.
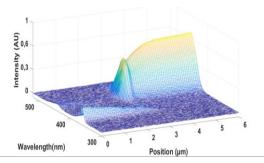

Fig. 5: Cross section of cathodoluminescence spectrum through a GaN based LED stack mesa

Thanks to this method, preventing a long and expensive process such as VTF LED, various surface treatments with or without dielectric capping were investigated. Results underline that as often reported KOH partly passivate. Contrary to numerous scientific publications, our first results seem to suggest that sulfur based treatments are irrelevant. Thermal Atomic layer deposition of Al_2O_3 enhance passivation even at low temperature.[2,3] From XPS measurements, it appears that Plasma Enhanced ALD of Al_2O_3 leads to higher interfacial GaN oxidation.[4]

Perspectives

Improvements require to determine the nature, the energy of surface states to adapt and focus surface treatments on the deepest. But, the biggest difficulty lies in performing measurements such as DLTS on mesa sidewalls.

RELATED PUBLICATIONS:
[1] Corentin Le Maoult, PhD thesis, to be published
[2] Le Maoult et al., in progress
[3] Jacopin et al., in progress
[4] Le Maoult et al., Analysis of InGaN surfaces after chemical treatments and atomic layer deposition of Al2O3 for µLED applications, Proc. of SPIE Vol. 11280 112801C-1

A novel degradation model for LED reliability assessment with accelerated stress and self-heating consideration

AUTHORS:
MT. Truong[1,2], L. Mendizabal[1], P. Do[2] and B. Iung[2]
[1] Univ. GrenobleAlpes, CEA-Leti; [2]Université de Lorraine, CRAN, UMR 7039

Light-emitting diodes (LEDs) are used in numerous "high reliability" applications. However, current methods to evaluate LEDs reliability introduce significant prediction errors, and requires implementation of accelerated aging test, which are "costly" for industrial applications. Thus, in order to develop an optimal test plan, the LED's degradation model needs to be studied carefully with the dependent factors. In this context, the self-heating, shown through the increment of junction temperature (T_j) during the test, remains one of the main influencing factors in the degradation process of LEDs. To face this challenge, this paper proposes a novel accelerated degradation testing (ADT) model considering the self-heating impact in the degradation process of LED

SCIENTIFIC COLLABORATIONS: This work is carried out mainly in collaboration with the Sustainable System Engineering department (ISET) of CRAN UMR CNRS7039, University of Lorraine.

Context and Challenges

Conventionally, thermal stress is often used to accelerate LED degradation using the Arrhenius model [1]. Indeed, using T_j, as thermal stress, is accurate for the LEDs' degradation rate modeling. However, T_j is not constant and may increase during the acceleration test due to the degradation impact [2, 3]. To sum up, there is a loop of thermal stress, subjected to a self-heating on the LED, which affects the degradation of LED over time. In that way, the self-heating phenomenon, shown through the increment of T_j, is an important issue and needs to be considered in the LEDs' degradation modeling and reliability assessment. However, very few research works are addressing this issue.

Main Results

So, our contribution leads to develop a novel ADT model considering the self-heating impact in the degradation process of LEDs. To highlight the added value of such a model, we first analyze the results of the experiment to show an increment in T_j due to the degradation of LED (Fig 1.a, 1.b). Then we model the self-heating impact mathematically. Next, the degradation model and the reliability assessment are formulated. Finally, we analyze some obtained results when applying the proposed model to the experimental dataset (Fig 1.b, 1.c).

It is identified that the degradation indicator of the LED $(X(t))$ which is determined by relation to the normalized light output, is a random variable. Figure 1.a illustrates first that the forward current leads to an increment in LED's junction. Then, it is found that T_j increases after the acceleration test. This result is in line with the issue underlined above on the T_j increase due to LED degradation. Thus, the T_j is the sum of three parts: the stress temperature (T_k), the increment of T_j due to the forward current (a) and due to the impact of the degradation $(f(X(t)))$. Then, this T_j is used in the Arrhenius model for modeling LED's degradation rate. Finally, the LED's degradation as a stochastic process and its cumulative distribution failure (CDF) considering self-heating are formulated [4]. The obtained results are then compared with the experiment values, Fig 1.c. It leads to consider that the CDF based on the proposed degradation model, which considers self-heating, is well-fitting with the experiment values. In contrast, without the self-heating consideration, the conventional model leads to a significant error in CDF calculation. Additional analysis on LED shows some small darkenings in the junction mesa, Fig 1.b. This failure mechanism in the junction region corresponds with the energy activation, about $E_a = 0.31eV$, which is found based on the model parameter's estimated value. Therefore, the estimation approach seems to be adequate.
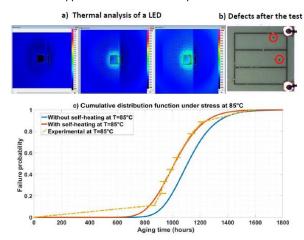

Fig. 1: Main results

Perspectives

In terms of prospect, one future work is to extend the proposed model for a more complex system (e.g., system-on-chip) with self-heating and thermal interactions between components and for deciding on the optimal design test.

RELATED PUBLICATIONS:
[1] W. Nelson, Accelerated testing: statistical models, test plans, and data analysis, vol. 257. Wiley-Interscience, 1990.
[2] Buffolo, M., De Santi, C., Meneghini, M., Rigon, D., Meneghesso, G. and Zanoni, E., 2015. Long-term degradation mechanisms of mid-power LEDs for lighting applications. Microelectronics Reliability, 55(9-10), pp.1754-1758.
[3] Ke, H.L., Jing, L., Hao, J., Gao, Q., Wang, Y., Wang, X.X., Sun, Q. and Xu, Z.J., 2016. Analysis of junction temperature and modification of luminous flux degradation for white LEDs in a thermal accelerated reliability test. Applied optics, 55(22), pp.5909-5916.
[4] Truong, M.T., Mendizabal, L., Do, P., Iung, B., 2021, June. A novel degradation model for LED reliability assessment with accelerated stress and self-heating consideration. In 2021 IEEE 71th Electronic Components and Technology Conference (ECTC). IEEE.

Assessment of 2D nano-semiconductors for color conversion: a further step towards high brightness full color micro-displays

RESEARCH TOPIC:
High luminance LED Micro-display, CdSe Nano-platelets, color conversion

AUTHORS:
E. Quesnel, A. Suhm, M. Consonni, M. Reymermier, G. Lorin, C. Laugier, M. Tournaire, P. Le Maitre, A. Lagrange, B. Racine

With the development of augmented reality (AR) market, there is an increasing demand for very bright full color micro-displays. Today, the GaN-based emissive devices are seen as the most promising technology. However, full integration of color pixels on a same display remains a technological bottleneck requiring alternative light conversion materials and processing. Here, we have synthesized and characterized color conversion photoresists based on novel core-double shell $CdSe_xS_{1-x}$ nano-platelets. The main output of this study is the outstanding blue-to-red conversion efficiency of such kind of materials and the ability to integrate them at wafer level on 9.5 µm-pitch arrays of blue micro-LED, paving the way to the manufacturing of future color LED micro-displays.

SCIENTIFIC COLLABORATIONS: NEXDOT company

Context and Challenges

The best solution for building a RGB LED micro-display is an array of blue micro-LEDs covered with blue-to-green and blue-to-red converters [1]. These converters are photoresist (PR) layers integrating photo-luminescent nano-semiconductors. However, their external power conversion efficiencies (EPCE) remain below the needs (≥25%) to exceed 50,0000 cd/m^2 white luminance.

Main Results

We have studied the conversion efficiency of PRs based on novel core-double shell $CdSe_xS_{1-x}$ nano-platelets (NPLs) developed by NEXDOT. Photoluminescence characterizations of PR layers was achieved and a theoretical model developed to predict the dependence of EPCE vs layer thickness (t) [2]. An example of EPCE dependence is given in Fig.1. We get a good theory-to-experience matching and an outstanding 35% EPCE with our novel red PR, beyond the state of the art. Similar measurements on green PR led also to significant EPCE (20%).

On top of this work, we have tested the ability to pattern the red PR using microelectronics tools. Successful integration of red pixels on a 9.5 µm-pitch passive matrix of blue micro-LEDs is shown in Fig.2. The color emission is more magenta than red since the 4µm-thick pixels only absorb 60% of blue but processing solutions to get denser pixels are under study.

Perspectives

Next step will be the co-integration of blue, red and green pixels on same matrix of micro-LEDs to demonstrate the manufacturing of high luminance full color micro-displays.
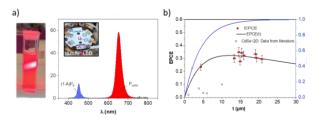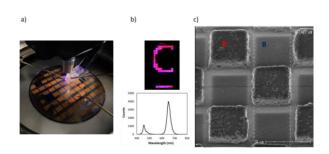

Fig.1. red NPLs, emission spectrum & EPCE.

Fig.2. Red pixel integration & emission.

RELATED PUBLICATIONS:
[1] E.Quesnel et al.; J Soc Inf Display. 2020;1–14. https://doi.org/10.1002/jsid.884
[2] E.Quesnel et al, Experimental and theoretical investigation of 2D nanoplatelet-based conversion layers for color LED microdisplays, Optics Express, 2021, https://doi.org/10.1364/OE.425907

Pixel Circuit for GaN Micro-LED control in Very High Luminance Applications

RESEARCH TOPIC:
GaN Micro LED, Pixel, Driver, Augmented Reality, microdisplay, High brightness, Pulse width modulation

AUTHORS:
M. Vigier, B. Dupont, T. Pilloix, F. Templier

GaN micro-LED technology offers high luminance level, which is a strong requirement for microdisplays used in augmented reality, as well as large display applications. Their electro-optical characteristics differ from the commonly-used OLEDs. So new circuitry with higher driving capabilities for the pixel control needs to be developed. This paper discusses the architecture of such a CMOS pixel, suited for GaN micro-LED control

Context and Challenges

Display devices are already found in many applications, and tend to spread more and more. They can be as large as a wall, or as small as a coin, but in every case, we expect them to enable good watching quality. Classic demand asks for very high resolution, low pixel pitch, high contrast, and high bit depth. In outdoor applications, or for large displays, high luminance is also an important issue.
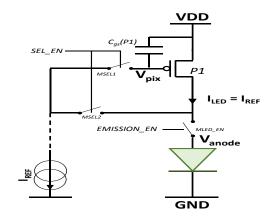
Main Results

For microdisplay, luminance at source level is at least 100kcd/m² to several MCd/m². But very few light sources can deliver such a luminance level, although needed in these applications. Despite a low maturity level, GaN micro-LEDs could be a good candidate, with high contrast, high brightness, high efficiency as well as good lifetime.
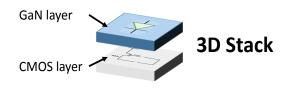
Implementation of an array of GaN micro-LEDs was demonstrated many years ago. High resolution array of GaN micro-LEDs have also been demonstrated, but don't provide the needed luminance for the whole array.
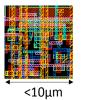
Perspectives

High resolution display devices require active matrix backplane to enable an accurate control of the array. This paper [1] discusses pixel control solutions that could be implemented, regarding the specificity of GaN micro-LED technology, as well as their maturity level.

Pixel driver circuit

3D Stack

Pixel Layout

<10µm

GaN pixel controlled with CMOS circuit. Left: 3D Stack principle, and right: CMOS layout

RELATED PUBLICATIONS:
[[1] M.Vigier, B.Dupont, T.Pilloix, F.Templier, "Pixel Circuit for GaN Micro-LED Control in Very High Luminance Applications", International Display Workshop (IDW), December 9-11 2020, Fukuoka, Japan.

Very high brightness, high resolution CMOS driving circuit for microdisplay in augmented reality

RESEARCH TOPIC:
Micro LED, Pixel, Driver, GaN, Augmented Reality, microdisplay, High Luminance, Pulse Width Modulation, HUD, Near-to-eye

AUTHORS:
M. Vigier, T. Pilloix, B. Dupont, G. Moritz

In augmented reality applications, high brightness at high resolution is crucial to guarantee a good user experience. Explorations on efficient light sources have already been undertaken, and GaN µLEDs is a good candidate. But micro-display driving circuits usually do not provide sufficient luminance level to offer good contrast against ambient light. We report the design and fabrication of a GaN LED microdisplay driving circuit enabling, to our knowledge, the highest brightness for such a pixel pitch and resolution. The driving circuit was designed in a 0.18µm CMOS process with 1640x1033 resolution. Each LED is controlled individually by a CMOS pixel of 9.5µm pitch. A monochrome green microdisplay enables more than WSXGA resolution and can reach 3.8MCd/m² for a fully ON micro-LED array.
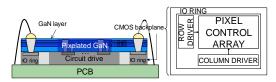
Context and Challenges
The trend on devices for virtual and augmented reality increases continuously, requiring high-resolution microdisplays at small pitches. In augmented reality applications, a sufficiently bright microdisplay is also a challenge, to offer contrast against ambient light, and allow a good user experience. Non-GaN microdisplay with driving CMOS were already presented, and show high resolution but limited brightness, up to 20kcd/m². Circuits with micro-LED GaN can demonstrate brightness reaching up to 2.2.107cd/m², but on single source measurement, or a limited resolution. Indeed, the challenge of scaling high brightness at high resolution and low pitch induces important power densities. Under those conditions, it is very difficult to guaranty good luminance uniformity across the array, because of voltage drop and lack of headroom for circuit drive.

Main Results
This work [1] focuses on the design of a CMOS microdisplay control circuit, capable of delivering sufficient power to enable high luminance at high resolution and reduced pixel pitch, along with an important luminance range, and adapted to GaN micro-LED technology. To our knowledge, this is the first circuit gathering all these aspects together.
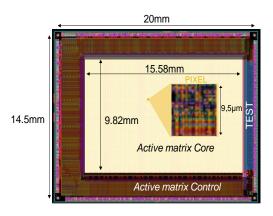
Perspectives
The designed CMOS is suitable for monochrome, bicolor and full color use, with multiple color mode and white temperature tuning. To our knowledge, this circuit is also the first enabling full color monolithic GaN array control

Pixel specification	Expected results	
	Value	Unit
Max. Brightness	3.8×10^6	cd/m²
Pixel pitch	9.5	µm
LED mismatch correction	5	bit
Pixel current	5 to 20	µA
Pixel voltage	5.5	V

Module Stack(GaN and CMOS) on PCB, CMOS circuit drive principle, pixel specifications

Top circuit and pixel layout

RELATED PUBLICATIONS:
[1] M. Vigier, T. Pilloix, B. Dupont, G. Moritz, «Very High Brightness, high resolution CMOS Driving Circuit for Microdisplays In Augmented Reality Applications" Midwest Symposium on Circuits and Systems (MWSCAS), August 9-12, Springfield, MA, USA, 2020,

Structure of a LIFI dedicated binary pixel array

AUTHORS:
Yoann Seauve, Margaux Vigier, Thomas Pilloix, Luc Maret, Gilles Sicard

In recent years, visible light communication (VLC) have attracted a lot of attention as the key component of LIFI networks. Alongside complex and cumbersome mono LED implementations, which are used in labs to achieve extremely high data rate transmissions, slower but much more compact matrix emitters can be found in the literature. In this paper, we discuss the choice of matrix architecture for data distribution and transmitter operation scheme.
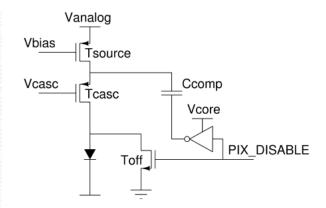
Context and Challenges

The constant increase of data generation and transmission, associated with the limited available radio frequency (RF) spectrum, make the implementation of new wireless links increasingly more difficult. Visible light communication (VLC) could be a new mean of wireless and high throughput data transmission.

Consequently, VLC has earned a lot of interest during the past years, as a complementary data link to RF based ones. They generate an optical signal of variable power, and the light intensity codes for the data to send. High data rate transmission requires the use of large electro optical bandwidth light source with a high current density withstanding. GaN based µLEDs are well suited for this kind of application.
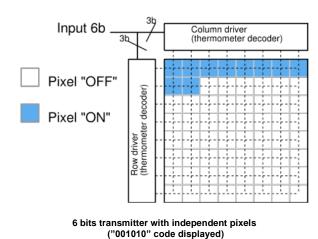
Main Results

We report the first design study on a fully integrated and high resolution (10 bits), multi LEDs VLC emitter. This work focuses on the pixel design [2], organization of such a pixel array [1], in terms of data distribution, LEDs to be turned ON strategy, power supply distribution and Frame rate enhancement strategy.

We report on the use of two subpixels per pixel to mitigate the Inter symbol Interference, and enhance pixel frame rate up to 333 MHz. We compare pixel arrays with independent pixels (Fig. 2) and weighted pixel groups. The former offers better conversion linearity when dispersed LEDs are used, and paves the way to an ultra-compact and high resolution LED array based VLC circuit for LiFi networks.

Pixel driver circuit

6 bits transmitter with independent pixels ("001010" code displayed)

RELATED PUBLICATIONS:
[1] Y. Seauve, M. Vigier, T. Pilloix, L. Maret, G. Sicard, « Structure of a LIFI Dedicated Binary Pixel Array" IEEE International Conference on Electronics Circuits and Systems (ICECS), November 23-25, Glasgow, Scotland, 2020,
[2] Y. Seauve, M. Vigier, T. Pilloix, G. Sicard, "Fast GaN µLED Pixel for Visible Light Communication Matrix Emitter" IEEE NEWCAS International Conference, Montreal, Canada, June 16-19, 2020,

Copper pillar based advanced packaging, for large surface and fine pitch Interconnections, applied to display devices

RESEARCH TOPIC:
Miroelectronic packaging for the field of display and lighting devices using 2D and 3D GaN pixels at 30 µm or less pitch.

AUTHORS:
A. Ait Mania, N. Caicedo, N. Miloud-Ali, F. Levy, F. Berger, T. Mourier, N. Raphoz, A. Gueugnot, P. Peray, L. Boutafa, D. Henry

The packaging step is of first concern in order to reply to the new hi tec electronic devices performances need. The Leti-Dopt challenge is to develop new solutions that can stand high input/output counts, density resolution needs with continuous decreasing pitch for monolithic active surfaces. The flip chip assembly using cu pillars bumps is one of the answer to these challenges. To give a high quality level to our customer in this study, we designed and manufacture a matrix of copper pillars interconnections, half million pixels at 30 µm pixel pitch to connect vertically the display array on its CMOS driver which command the emitting GaN pixels. The extensive work allow us to deliver a functional demonstrator qualifying our customer's display technology.

SCIENTIFIC COLLABORATIONS: The work was totally conducted inside the CEA-Leti labs and clean rooms facilities, in collaboration with the technical staff of our final customer.

Context and Challenges

The Gallium nitride, since the invention of the Blue LED by the professor's Shuji Nakamura team take more and more place in the lighting and display devices. Its High luminance, coupled with the quick development of conversion materials to build filters for both white light and colored screens make it a serious candidate to eliminate the older pixel technologies based on the use of OLeds or LCD.

The final customer here is an actor of the display market, and the project was made in the CEA-Leti microelectronic facilities for all the technological and test operations. The work concerned the dimensionning, the design and the fabrication of robust interconnections elements to connect reliably a display matrix, GaN based whith its CMOS driver.the hybridization process should not damage the active layer and stand to many post technological step after the flip chip assembly. To comply to all these requirements, a large work was done on how to develop a robust underfilling process, totally compatible with the copper pillars density count and geometry. The copper pillars stacking consist in a copper layer covered by a Nickel barrier and a final caping with SnAg fusing material. The manufacturing was made with ECD (ElectroChemical Deposition) tools. The total height represent about 20 µm.

Main Results

The development of the Cu bumps lead us to reach a good coplanarity level, better than 2 µm which is of importance at the hybridization step. We overcomed many critical steps, as a clean etching of the copper seed layer without undercut defect , a uniform shaping of the SnAg solder layer, a deoxidization step of the tin oxide prior to the hybridization, and the right thermocompression profile with a maximum temperature peak of 250 °C and an arm force > 20 Kg. To complete these parameters, we modified the SiC tool of our SET FC300 pick-and-place equipment in order to match the shape of the top die and give uniform pressure on all the 4 cm² surface of the emissive area. We developed a thermal dehybridization tool that help us to see clearly the wetting yield of Cu bumps on the top UBM pads. The characterizations made in the mil std 883 respect, showed results at the state of the art with a shear force values > 100 Kg, the interconnection quality was checked with a great number of cross sections that show the cu bumps and UBM all along a bumps line.

Perspectives

In this R&D large work, we developed and qualified all the critical steps for the packaging of 4 cm² display devices at 30 µm sub-pixel pitch and more than 100 000 pixels. Several functional demonstrators were delivered at the end of the project. It open the way to more agressive resolutions lower than 30 µm pitch and larger than 4 cm² by using monolothic substrates or by a joining techniques. however, an indutrialization work is mandatory in order to tightened the working parameters to a level compatible with a mass production.

Fig. 6: High luminance micro display with GaN pixels @30 µm sub pixel pitch

RELATED PUBLICATIONS:

[1] Marion Volpert,Dyvia Taneja,David Henry,Tarik Chaira,Fiqiri, Hodaj"Cu pillar as interconnect for 10 µm pitch and below,fabrication issues and assembly". ESTC 2018.

Curved microdisplays, impact on visual systems

RESEARCH TOPIC:
Curved microdisplay, OLED microdisplay.

AUTHORS:
S. Charriere, P. L. Joly, B. Simon1, S. Nicolas, F. Zuber, D. Henry, O. Haeberlé2

Curved image sensors have proved to be useful to improve optical systems thanks to a direct correction of field curvature. It allows either to remove the field lenses and thus having systems that are more compact or, to improve the image quality for the same number of lenses. This work explores the impact curved microdisplays can have on visual systems. Future Head-Mounted Displays (HMD) have to be more compact, with gains in luminous flux and image quality, all at once. Curved microdisplays can have an impact on all these challenges and can be major components in future HMDs

SCIENTIFIC COLLABORATIONS: [1] LP2N, CNRS UMR 5298, Université de Bordeaux, Institut d'Optique Graduate School, Talence France, [2] IRIMAS UR UHA 7499, Université de Haute-Alsace, Mulhouse, France

Context and Challenges

In imaging systems, the design has little constraints on the pupillary conjugation while in visual systems, the eye forces the exit pupil to be real and far, leading to greater aberrations. In parallel, HMDs tend to have wide field of view. The main challenge is to correct for both, while maintaining a compact systems. Lastly, for Augmented Reality (AR), the luminance losses are another issue. This work aims at analyzing how curvature is able to improve visual systems.

Main Results

Curved microdisplays, as the CEA-Leti prototype presented on figure 2, can improve optical systems in three ways. First, it is a better fit of paraxial conjugation, thus reducing the gap between the paraxial design and the final one. Second, it directly corrects for field curvature that is crucial for off-axis HMDs where only few controls on optical index are left, which are usually a major way to correct for it. Third, it can enhance the luminous flux coupled from the microdisplay toward the optical system, by reducing the apparent angle between pixels and pupil, and orientate the most powerful portion of the flux toward the pupil (figure 1).
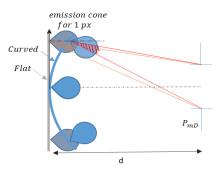

Fig. 1. Gain in luminous flux for a curved microdisplay

Fig. 2. Curved MICRODISPLAY CEA-LETI prototypes

Perspectives

CEA-Leti is now working on the development and the fabrication of a prototype to demonstrate our capabilities with some specifics optical protocols to characterize the obtained visual systems.

RELATED PUBLICATIONS:
[1] S. Charrière, P. L. Joly, B. Simon, S. Nicolas, F. Zuber, D. Henry, O. Haeberle, "Curved microdisplay, from optical design to mechanical study: impact on form-factor and light efficiency in visual systems", SPIE Strasbourg, Proceeding (2020)

O8 | PHD DEGREES AWARDED IN 2020

- **Baptiste CARON**
- **Axel CLOUET**
- **Lucas DUPERREX**
- **Gabriel JOBERT**
- **Thomas LAUWERS**
- **Basile MEYNARD**
- **Yoann SEAUVE**

BAPTISTE CARON

UNDERSTANDING OF OPTICAL LOSSES AND CONTRAST IMPROVEMENT OF TOP-EMISSIVE OLEDS

Since their discovery in the 80's, OLEDs (Organic Light Emitting Diodes) have established themselves as a key technology for display applications. They enable to achieve flexible or transparent OLED display panels. Organic semiconductors are intrinsically emissive and OLED therefore do not require backlighting unlike LCD monitors. This allows the fabrication of compact and lightweight devices and make very high display resolutions achievable. All these strengths are especially useful for the realization of micro-displays, developed for many years at CEA-LETI and used in nomadic display devices (augmented reality glasses, or AR).However, optical losses within the OLED stacks strongly limit the light power and the efficiency of these devices. For a conventional OLED, 80% of the light emitted within the device is lost. However, high luminance (typically 10-20 cd/m²) is required for AR applications to obtain a good contrast with the ambient outdoor light. The efficiency must also be as high as possible in order to minimize the battery weight of such mobile devices. A dedicated OLED device for studying emission modes has been created in this work in order to experimentally measure the sources of optical losses present in the top-emission OLED structures used in microdisplays. A nano-grating has been achieved by photolithography on top of the top-emitting OLED thin layer encapsulation, made by atomic layer deposition (ALD). This grating allowed to observe two of the guided modes contained in the microcavity of the OLED. It is the first time that such an observation is made on this kind of OLED which emits light from the top of the structure. An absorbing cathode has also been developed to improve the contrast of these OLEDs. The chosen material is a cermet (ceramic/metal) composed of silver and tungsten oxide (Ag:WO3 with a thickness < 20 nm). A study of the optical, electrical and morphological characteristics of this material allowed to realize OLEDs devices with improved contrast without adding a circular polarizer. The absorption of the cermet coupled with the cavity effect of the OLED strongly limits the reflections due to ambient luminosity.
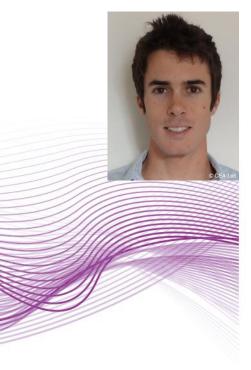
AXEL CLOUET

GEOMETRY FOR COLOR OR MULTISPECTRAL IMAGE SENSORS OPTIMIZATION IN NOISY CONDITIONS

Color and multispectral image sensors contain several acquisition channels characterized by their spectral responses. On one hand, the choice of these ones influences the functional performance of the sensor by changing its color and spectral accuracy. On the other hand, it affects noise amplification occurring when raw images are processed. This thesis contains a geometrical analysis of this phenomenon and proposes a method to optimize spectral responses. Multispectral images allow to simulate raw acquisitions from theoretical sensors and to test processing steps. Using an acquisition bench, a new dataset has been published containing 22 multispectral images covering the absorption range of silicon (400-1050 nm). Then, i developed a geometrical approach to describe noise amplification based on a graphical representation of signals/noise at raw, spectral and color levels. I concluded that inter-channel correlations are the main cause of the amplification. Based on this geometrical representation, I created a simple decorrelation method respecting positivity constraint, adapted to the computation of theoretical spectral responses. I used this method to compute optimized responses for a color sensor and I extended the principle to multispectral applications. To go further, I used a model of mesopic vision domain to relax colorimetry in a controlled way while increasing signal to noise ratio of the image. Then I showed that the geometrical approach could be extended to other issues like image demosaicing.

LUCAS DUPERREX

DEVELOPMENT OF A STRESS COMPENSATING SUBSTRATE AND ASSOCIATED PROCESSES TO PRODUCE LARGE INFRARED DETECTORS IN THE CONTEXT

Two critical thermomechanical parameters have been studied at the operating temperature of 100 K in order to manufacture very large format of infrared detectors: the level of residual stress in the semiconductor material HgCdTe and the planarity of the focal plane array. First, the two types of detector currently produced at Lynred have been characterized, both through experimental measurements (X-ray diffraction residual stress analysis and planarity measurements, both at room temperature and at 100 K) and numerical simulations (analytical and finite element modelling), so as to clearly understand their thermomechanical behavior. Then two improved structures have been defined, prototyped, and studied with the same approach, in order to finally conclude on the most relevant for very large formats (spatial applications).
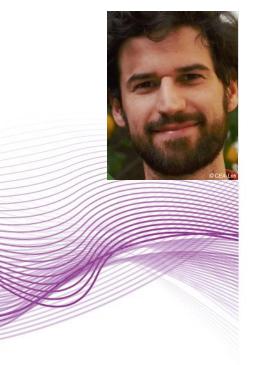
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GABRIEL JOBERT

CONTRIBUTION TO THE DEVELOPMENT AND MINIATURIZATION OF OPTICAL PARTICULATE MATTER SENSORS

This thesis is a contribution to the scientific community for the development of tomorrow's optical Particulate Matter (PM) sensors 'on-a-chip', which should be miniaturized, portable and inexpensive while being at the same time sensitive and accurate. The development of such sensors addresses the current sanitary and environmental issues related to air quality monitoring. What should such a sensor look like, which designs are successful, which ones are not? What are the difficulties we did not imagine we would encounter? Those are the questions we have tried to answer, by exploring three novel designs of optical particle counters (OPCs).

A first prototype has been developed, and comprises a custom CMOS image sensor with a traversing air channel. A particle, flowing in the channel, crosses a light beam and a scatter a specific pattern, which is recorded by the image sensor in a lens-less configuration.

Then, an improved mode of imaging is studied with a second prototypes that involves a monolithic, millimeter-sized glass assembly of lenses and mirrors. This miniature optical system is directly coupled with the holed image sensor. For both the first and second prototypes, experimental images of calibrated polystyrene beads are used to retrieve the diameter and refractive index of particles, using dedicated image processing softwares.

Finally, by the means of a third prototype, we explore how an optical resonant cavity is perturbed by the presence of a particle. In particular, open vertical cavity that involves dielectric mirrors such as distributed Bragg reflectors and photonic crystal slab mirrors are studied. Understanding the mechanisms involved in the perturbation of the cavity, enables the design of a cavity-enhanced OPC, where the perturbed cavity mode is analyzed by transmission imaging.

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THOMAS LAUWERS

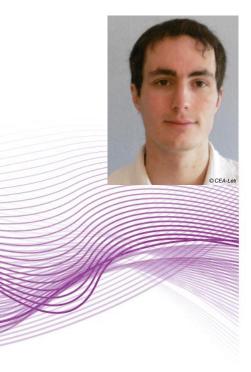## OPTICAL TRANSDUCTION METHODS FOR THE PHOTOACOUSTIC AND PHOTOTHERMAL DETECTION OF TRACE GAS

This thesis focuses on the study of Fabry - Perot cavities, used as optical transduction alternatives for the resonant detection of gas traces, by the photoacoustic and photothermal method. The principle of measurement is based on the shift of the optical cavity resonance, induced by acoustic or thermal perturbations. Two approaches have been studied, then the transduction systems were fabricated and characterized, and finally implemented in sensors for trace gas detection. The first approach is based on a Fabry - Perot cavity of low finesse assembled at a fiber tip and interrogated by a low - cost laser diode emitting at 1.55 µm. The second mirror of the cavity is a mechanically resonant cantilever beam, suitable for the measurement of weak acoustic signals. In a first step, a reduced element model was set up to predict the coupled behavior of the mechanical structure, the surrounding fluid, and its interaction with the excitation light source in the sensor. The model has been successfully compared with resolutions performed by the finite element methods and experimental characterization results. The limit of detection at the resonance frequency of the system, is of the order of 2 $\mu Pa/\sqrt{Hz}$. Finally, the transduction system was integrated in a photoacoustic sensor and calibrated on a NO absorption line, leading to a detection limit lower than 10 ppb. The second approach, more innovative, consists of a phase shifted Fabry - Perot cavity, fabricated on an optical fiber and of very high quality factor, stabilized by a Pound-Drever-Hall optical locking technique. The implemented optical locking permits to be extremely sensitive to optical resonance shifts, which depends here mainly on thermal perturbations. After an implementation of the reduced element model, adapted to this new problem, the optical guide is mounted in a photothermal sensor and tested for the detection of atmospheric CO_2. The limit of detection, estimated by extrapolation, is here in the order of one ppm.

BASILE MEYNARD

AUGMENTED REALITY DEVICES BASED ON WAVEGUIDE / HOLOGRAM COUPLING

The CEA-Leti research institute recently developed a novel retinal projection concept. The projection system is embedded on transparent glasses for augmented reality (AR) applications. The CEA-Leti concept aims to overcome current limitations of already commercialized AR glasses, such as complex and bulky optics. It uses a self-focusing effect to generate images directly on the retina of a user without any artificial optical components, allowing the creation of a fully integrated and portable device. The concept is separated into two main parts: an integrated photonic circuit and an analog hologram. This thesis focuses on the first part, i.e. the photonic circuit. The hologram is developed in parallel of the thesis by other team members. The thesis allowed to design, fabricate and experimentally characterize a design kit made of basic photonic components (ex: singlemode waveguide, various couplers active optical switches...). They can be assembled in order to design the complex photonic circuit of the final retinal projection device. The photonic components are made of Si3N4 and were optimized to work specifically at λ = 532 nm (green). They were fabricated in clean rooms on 200 mm wafer platforms at the CEA-Leti and STMicroelectronics fabrication facilities. The characterization of the components was carried out with an automated optical prober and a goniometer. The goniometer was entirely designed and fabricated during the thesis for the purpose and the specific needs of this project. Finally, a simple applicative photonic circuit was designed to study the interaction between our photonic circuits and the analog hologram.

YOANN SEAUVE

STUDY AND DESIGN OF A DRIVING CIRCUIT FOR GAN LED MICRODISPLAYS

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Recent advances in the field on inorganic LEDs, allow for manufacturing of GaN LEDs at micrometer scale. These optical devices, which were initially only manufactured with large dimensions, can be associated to a CMOS driving circuit to form micro-displays. GaN based micro-LEDs offer a maximum brightness and a commutation speed, well above other LEDs technologies used at micrometer scale. However, they also have specific electrical characteristics, such as reduced efficiency and large dispersion of behavior, when used with a reduced current. Consequently, driving methods commonly used with other types of LEDs are not appropriate for the control of such devices. This thesis focusses on the design of pixel driving circuits suitable for micro GaN LEDs, both in terms of implemented driving method and footprint compliance with the size of used LEDs. The first part of this work focusses on display applications, with a compact pixel matrix exploiting LEDs high brightness, while offering a large resolution. A PWM driving scheme, which implies sporadic operation of the LEDs under high current, is chosen to deal with LEDs specificities. In order to insure low silicon footprint despite the relatively high complexity of PWM driving, a 3D manufacturing of the circuit is introduced. A derivative of the CoolCube 3D technology that is developed by CEA Leti, is considered to manufacture a micro-display on three superposed levels. The driving circuit is split between the two first levels, made a CMOS circuit with different types of transistors. An array of GaN LEDs form the third level for the display. The second part of this thesis focusses on exploiting the reduced commutation time of the GaN LEDs. The ability to generate a high frequency optical signal is appropriate for building visible light communication emitters. Several free space optical communication emitters reported in the literature use a single GaN LED to transmit data at several Gb/s. Although, these single LED emitters are very fast, they are cumbersome and complex to build. Other emitters, based on a group of LEDs each emitting a part of the optical signal, forms an alternative solution. Even though data transmission is currently slower using these emitters, matrix based emitters are much more compact. This work introduce the design of a binary pixel, which make the LED switch between its two possible states, ON and OFF. Thanks to a LED introduced parasitic capacitance compensation method, this circuit reaches a 333 MHz operation frequency. Finally, a study of the best pixels organization inside the array led to a thermometer type of pixel control. The resulting association between each input code and the activated pixels insures the conversion monotonicity. It also shows a better linearity than other matrix control schemes with simpler implementations.
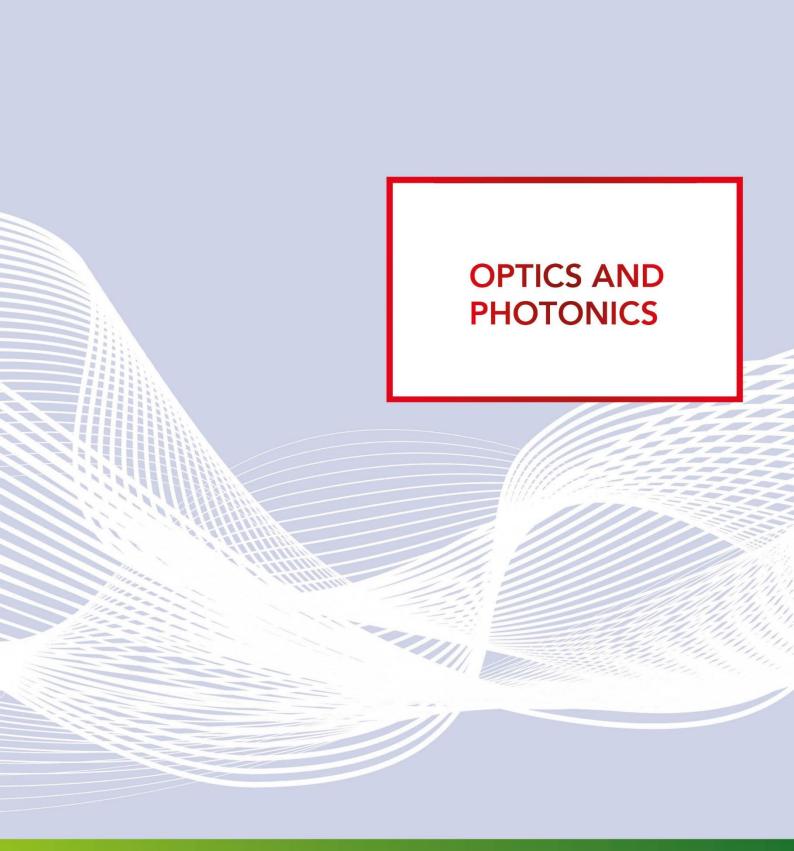
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OPTICS AND PHOTONICS

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