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 1,870, a portfolio of 3,200 patents, 11,000 sq. meters cleanrooms, and a rigorous IP policy, CEA-Leti has launched 71 startups and is a member of France’s Carnot research network. Based in Grenoble, France, the institute has offices in Silicon Valley and Tokyo.

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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.

www.cea.fr/english

CEA-Leti at a glance

450 publications per year

ISO 9001 certified since 2000

1,870 researchers

114 European projects

3,200 patents in portfolio

Based in France (Grenoble) with offices in the US (San Francisco) and Japan (Tokyo)

11,000 sq. meters of cleanrooms 100-200-300 mm wafers

300 industrial partners

71 startups created
Within 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

We work with both industrial and academic players. 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, microelectronics, advanced nano-fabrication, integration and packaging, while accounting for system requirements.
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

We work with both industrial and academic players. 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, microelectronics, advanced nano-fabrication, integration and packaging, while taking into account system requirements.
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Year 2021 have seen the Covid-19 crisis go away. Today, its not-yet-resorbed consequences combine with exacerbated geopolitical rivalries. The war in Ukraine polarized the world, and consolidated at least some of historical international political blocks. Today, the economical exchanges, supply chains, access to natural resources and advanced technologies are all part of modern warfare. Free and unlimited economic exchanges evolve back into highly politicized block economies. The Covid-19 economic rescue/re lief plans and worldwide hike in military spending create strong inflationary pressure. Central banks are walking a tight rope trying to control the inflation without sending the economies into recession.

One of the many consequences of the COVID-19 pandemic has been spiking sales of consumer-electronic products just as there was a slowdown in chip production, particularly in Asia, where much of the $600bn industry has shifted in recent years. Two factors condition the current semiconductor crisis: the disruption of supply following the Covid pandemy, and the Sino-American competition inducing access restrictions to the Chinese players by the United States.

The five largest semiconductor companies are American or America’s Asian allies (Korea, Taiwan). TSMC fabricates over 85% of world’s advanced semiconductors (lower than 7 nm node). The recent U.S. sanctions on key Chinese companies caught many semiconductor foundries in a crossfire. For example, TSMC stopped delivering advanced node chips to Huawei, as it also halted the production of 28 nm Russian-designed Elbrus processors for Russia. China has no longer access to foreign technologies. It faces bottlenecks in electronic design automation and extreme UV lithography (Dutch ASML) allowing crossing the 7 nm threshold.

Facing the One China principle, the western world is building a resilience to the worst-case scenario of Taiwan invasion by China. A wave of capital expenditures submerges the semiconductor industry, mostly for the advanced node fabs built outside of Asia. A 10-year cost of a semiconductor fab in the US is 30% higher than in Taiwan and South Korea, and 50% higher than in China. Even at such a premium, advanced fabs are being built in the US and in Europe, funded by combining federal American and European Union CHIPS acts with direct investment from the fab companies.

Current semiconductor crisis shows once again the strategic, vital, and growing importance of micro-nanotechnologies in all aspects of our lives. The Optics and Photonics division of CEA-Leti responds to the increased demands from our partners/customers in various microphotonics technologies, from infrared imagers, optical environmental sensors, guided and free-space optical datacoms, to wearable computer displays. We play an active role in rebuilding European microelectronic industry.

In this annual scientific report, you will find examples of our results that appeared in open publications. These examples are just a small part of our rich and dynamic developments. Contact us if you wish to know more about photonics at CEA-Leti.
KEY FIGURES

345 persons overall total workforce
235 permanent R&D engineers and technicians
45 PhD students and post docs

76 patents filed in 2021
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
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, IWDDC, NDIP.
Members of the IRDS roadmapping initiative, AFNOR French standards body.
• n-on-p extrinsic MWIR HgCdTe diodes operate at higher temperatures
• Optical persistence on HgCdTe SWIR imagers is explained
• HgCdTe avalanche photodetectors - hole multiplication is observed
• 2k x 2k HgCdTe arrays over perform in an astronomy application
• High-impedance surfaces allow above-IC integration of cooled bolometric imagers for 350 µm wavelengths
Context and Challenges

Quantum infrared detectors require to be cooled down to cryogenic temperature in order to obtain acceptable performances in terms of dark current as well as dark current noise. The increase of the operating temperature of infrared detectors is a main challenge, as it could allow to reduce the Size, Weight and Power-Cost (SWAPc) associated with the cooling system.

For HgCdTe based photodiodes, one of the technological solutions to reduce the dark current is the extrinsic p-type doping. This type of doping allows to reduce the Auger contribution on the dark current compared to a p-on-n photodiode. The theoretical reachable gain in terms of dark current at constant doping is modelled by the ratio between the Auger 1 and 7 generation coefficients $\gamma$. A large $\gamma$ value enables to reduce the dark current at constant doping or to obtain a constant dark current with a higher doping compared to p-on-n photodiodes. The value of $\gamma$ has not yet been clearly determined in literature which is why the achievable performances of an n-on-p extrinsic photodiode technology is still a subject of research.

Main Results

N-on-p extrinsically doped photodiodes and material from 2 wafers with 2 doping levels, have been formed and characterized through dark current, dark current noise, Hall effect and minority carrier lifetime by PhotoLuminescence Decay (PLD) measurements [1]. A dark current slightly higher than p-on-n photodiodes has been measured with the lowest doping level. This observation and carrier lifetime results are consistent with a potential gain in dark current or doping of a factor $\gamma$ around 10. The 1/f noise at high temperature was found to be the lowest reported for IR photodiodes. These results show that this technology has the potential to form high operating temperature imagers.

Perspectives

The observation Auger 7 limitation of the dark current and the low 1/f noise opens the perspective to form high performance imagers at high operating temperature. The results show on a margin for optimization through the reduction of the doping level. Reaching a doping level of $1 \times 10^{15} \text{cm}^{-3}$ could allow to increase the BLIP temperature to 190K at F/4. Such high operating temperature would be a major breakthrough in the field of SWAPc focal plane arrays.

Fig. 1: Dark current noise as a function of the dark current compared with Tobin’s model and theoretical shot noise (I refers to the dark current).

**RESEARCH TOPIC:**
High operating temperature MWIR HgCdTe photodiode development through p-type extrinsic doping

**AUTHORS:**
M. Soria, P. Bleuet, F. Boulard (DPFT), J.-L. Santailler (DPFT), F. Marmonier (DPFT), L. Bonnefond (DPFT), T. Pellerin, G. Poisson and J. Rothman

**RELATED PUBLICATIONS:**
Model and characterization of persistence on HgCdTe SWIR imager

RESEARCH TOPIC:
Persistence, HgCdTe, SWIR detector, astronomy, modelling

AUTHORS:
T. Le Goff, T. Pichon¹, N. Baier, O. Gravrand, O. Boulade¹

Context and Challenges

Detectors in astronomy. After a bright illumination, the signal of previous acquisitions pollutes the following ones. To mitigate the impact of this phenomenon, astronomers must calibrate persistence on every detectors. However, persistence models are empirical ones based on multi-exponential or power law fitting. Models closer to the physics of persistence is needed to improve the efficiency of the calibration. It would also help identify technological step responsible of this phenomenon.

Main Results

We develop an analytical model based on trapping/emission processes of electrons from the space charge region of the diode. Considering alloy and ionic properties of HgCdTe, defects are more likely to generate an energy distribution in the band gap instead of single levels. With this hypothesis, persistence signal could be compared to data obtained on detectors built in house at CEA-Leti. The model shows good agreement with data but reaches its limits to explain high persistence amplitude observed on first generation detectors.

Perspectives

Part of persistence signal is well described with this model, but other contributors should be included in the following. For instance, traps at the passivation interface would have a non-negligible contribution.

For persistence calibration, our model could be completed with capture properties of traps. This would allow to also calibrate its charging phase.

RELATED PUBLICATIONS:
First evidence of hole multiplication in HgCdTe APDs

Context and Challenges
HgCdTe APDs have until present been characterized by an exclusive electron initiation of the avalanche process that is responsible for their exceptional performance to conserve the amplitude and temporal information of the photon signal at high gain. These properties have opened a new observation window for light that have found applications in variable domains such as free space optical communications, atmospheric Lidar and quantum optics. In order to meet the most demanding requirements in such applications, the present challenge in the development of these detectors is to reduce the response time and the noise (dark and multiplication noise) while increasing the APD performance through the development of new APD architectures and process. This effort has in particular allowed developing APDs with high gain and fast response over a larger areas. Response time and gain measurements on some variants of these APDs have yielded results that are consistent with a first observation of hole multiplication in HgCdTe APDs [1].

Main Results
The APD gain and response time have been characterized using impulse response time measurements at T=300 K. The results of these measurements are shown in Fig. 1. The APD gain has been estimated from dark current measurements and from the variation of the integral amplitude of the impulse response time (vertical gain). It can be seen that these estimation give a similar gain that increases exponentially at low reverse bias. At higher reverse bias, both curves show a steeper than exponential increase, with a steeper increase for the vertical gain. The origin of the additional gain is evidenced from the variation of the impulse response at low bias, the impulse response time is independent of the reverse bias and gain. The increased gain at higher bias is due to a strong increase of the response time. Such increase in response time, associated with an increase in amplitude, is consistent with an onset of hole multiplication that re-initializations the avalanche process and generates a stronger but strongly delayed signal. The observed variation of the gain and response time can be modeled with the hypothesis that the hole multiplication occurs preferably at their exist of the junction and do consequently re-initiate a full electron avalanche. The additional excess noise to the multiplication process can, in this picture, be modelled using a Markovian birth chain and the first modeling results show on a low impact on the excess noise factor $F_e$ expected to be lower than 1.5.

Perspectives
The observation of hole multiplication is an important milestone in the understanding of the physics of HgCdTe APDs. It will limit the performance of the HgCdTe APDs in application that requires the highest bandwidth and lowest multiplication noise. However, the observed increase in gain can be used to boost the gain at lower reverse bias and dark current. Such gain boost can find use to increase the detection efficiency of single photons at reduced dark count rate.

RELATED PUBLICATIONS:
Fabrication and characterization of a high performance NIR 2kx2k MCT array at CEA and Lynred for astronomy application

RESEARCH TOPIC:
IR imaging, Astronomy, HgCdTe, ultra low flux, large format

AUTHORS:
O. Gravrand, O. Boulade, C. Lobre, J.L. Santailler, T. Pichon, N. Baier

For several years now, LYNRED, CEA-LETI and CEA-IRFU have been involved in the development of large area, very high performance NIR retinas for astronomy, in the context of the ALFA program (Astronomical Large Format Array). It aims at demonstrating the ability to produce in Europe low flux 2kx2k arrays exhibiting the very high performances required by science applications. In this context, high performance means very low dark current (below 0.1 e/s/px) with high QE (above 80%). LETI and LYNRED succeeded this year in the fabrication of a 2kx2k array, with very high uniformity as characterized at IRFU. One of those arrays will be used on the CAGIRE camera of the SVOM mission, aiming at observing afterglows of gamma ray bursts.

SCIENTIFIC COLLABORATIONS: 1CEA IRFU (Saclay), Lynred (Veurey Voroize)

Context and Challenges
The HgCdTe (MCT) material system is well known to provide the high QE as well as very low dark current required for astronomical applications. Such high performances has been demonstrated several years ago within our lab onto small size test arrays [1] and the ALFA program aimed at demonstrating the ability to scale this technology to very large formats such as 2kx2k 15µm pitch. This represents a serious challenge as the final chip is 3x3cm² (see Fig. 1), much larger than the usual 1cm² class chip. LETI was in charge of the absorbing layer process while Lynred was responsible for the packaging with the Si read out circuit. Last but not the least, CEA-IRFU was in charge of the chip final characterisations and performance assessment.

Main Results
The delivered chip meets all the performances required by ESA. Indeed, the measured QE is above 70% over the whole spectral band of interest (from 0.9 to 2µm). After optimization of the diode process and the layer growth conditions, the dark current has been strongly reduced down to ultra-low values (Fig 2.). Indeed, at 100K, the dark current histogram of the 4 million pixels peaks at 0.002 e/s, i.e. one electron every 10 minutes leaking in the system.
Furthermore, other second order figures of merit have also been considered in the process optimization, such as persistence (factor 10 improvement), pixel to pixel cross talk (below 0.5% lateral coupling), and even space radiation robustness [3].

Perspectives
The resulting array will be used into the CAGIRE IR camera mounted in a Telescope in Mexico, in order to observe gamma ray bursts within the SVOM mission.

Acknowledgements
ESA, H2020 and FOCUS labex

Fig. 1: Fully packaged 2048x2048 ALFA array
Fig. 2: Dark current mapping @ 100K

RELATED PUBLICATIONS:
High-Impedance Surfaces for above-IC integration of cooled bolometer arrays at the 350-µm wavelength

Context and Challenges
Silicon bolometers cooled at 50-300 mK are high-performance sub-millimeter wave detectors used in astrophysics. In the frame of the SPICA space observatory project, polarimetric bolometer arrays operating in the 100-200 µm band have been developed. They are integrated on a CMOS read-out integrated circuit (ROIC) for low noise detection and signal multiplexing to the higher temperature stages. This above-IC integration scheme, i.e. fabrication on CMOS ROIC wafers, does not allow thick film processes, which would be normally required to scale the design to longer wavelengths since these detectors use a classical quarter-wavelength optical cavity.

High Impedance Surfaces (HIS) have been investigated for the above-IC integration of 350-µm (λ₀) detectors [1]. HIS are sub-wavelength periodic metallic structures with a very low thickness designed to generate a reflection coefficient close to +1. They are manufactured with standard materials.

Main Results
Prototypes have been designed, manufactured and characterized at 300 mK (optical absorption at 100-600 µm wavelengths) to demonstrate the feasibility and performance in the targeted wavelength and temperature range. The optical absorption is performed with superconducting thin-film Ti/TiN dipoles representative of future bolometers. These absorbers are placed above an optical cavity made of the HIS with a thickness of 13 µm only, i.e. less than λ₀/25 and much thinner than classical quarter-wavelength optical cavities. An optical absorption above 78% in linear polarization is obtained over a bandwidth of about 100 µm and a very good polarization discrimination is demonstrated (Fig. 1). An accurate electromagnetic finite-element model was developed to analyze the absorption in each material and in different temperature ranges.

Perspectives
The on-going work is focused on the development of actual bolometer detectors at 350 µm using this HIS concept and based on the detector technology developed for the SPICA project. The targeted applications are imaging focal plane arrays for future space observatories but also ground telescopes, such as the ARTEMIS camera on APEX telescope (Chile).

RESEARCH TOPIC:
Mm-wave and THz detectors

AUTHORS:
L. Dussopt, A. Aliane, H. Kaya, V. Goudon, L. Rodriguez¹, C. Delisle¹, V. Revéret¹, A. Poglitsch², E. Gümüs³, C. B. Winkelmann³

SCIENTIFIC COLLABORATIONS: ¹CEA-IRFU, ²Max-Planck-Institut, ³Institut Néel, Labex FOCUS (ANR-11-LABX-0013)

RELATED PUBLICATIONS:
Deep learning algorithm processes quad-pixel plenoptic light-field images

Parasitic coupling in 3D sequentially integrated CMOS imagers can not be neglected

Novel design of image-processing ASIC neural network accelerator is more versatile and efficient

Edge-Boxes algorithm employed in embedded smart-image-systems
Deep learning applied to quad-pixel plenoptic images

RESEARCH TOPIC:
CMOS image sensors, plenoptic, quad-pixel, image processing, deep-learning, neural network

AUTHORS:
J. G. Chataignier, B. Vandame, J. Vaillant

We developed dedicated image processing for quad-pixel plenoptic sensor. Unlike conventional pixels, quad-pixel consist of 2x2 sub-pixels placed under a micro-lens and records the light field instead of only radiance on the image plane. At first, we model the image formation with these pixels and we perform pixel-level simulation to take into account the diffraction inside the quad-pixel. This allow us to generate a dataset of realistic synthetic images. Then we develop new ways to process such quad-pixel images based on deep learning.

SCIENTIFIC COLLABORATIONS: 1 Interdigital

Context and Challenges
A plenoptic image sensor not only records the radiance on the image plane, like conventional image sensor, but also the light field. This additional information is customary used to estimate depth on the image. We focus on quad-pixels, which are the minimalistic version of plenoptic pixels, consisting of 2x2 sub-pixels placed under a micro-lens. Dedicated image processing have to be develop to optimally use the information encoded by these quad-pixels. This require sample images. However, there is no quad-pixel sensor available. Therefore, in parallel to demonstrator fabrication, we generate a dataset of realistic synthetic images by accurately modelling the image formation, taking into account not only the main lens, but also the diffraction at pixel level. Once the dataset is available, we consider three processing: dedicated color demosaicing, correction of pixel-level diffraction and depth estimation. We focus on convolutional neural networks (CNN) and deep-learning.

Main Results
Based on previously developed simulation framework [1], we are able to generate realistic synthetic images based on main lens description and quad-pixel structure. Here we consider smartphone-type compact camera.

![Synthetic Image](image1)

**Fig. 1:** (a) Synthetic image, (b) associated depth-map

The advantage of synthetic image is the capability to simulate the image but also the ground-truth depth-map (Fig. 1) or the diffraction-free image. For color demosaicing, we compare individual sub-aperture image demosaicing using state of the art CNN and our ResNet CNN taking the four sub-aperture image at once and delivering the color sub-aperture image. Our network 25% lighter and slightly better than reference CNN.

For diffraction compensation, two network architectures are considered: bottleneck ResNet and 3 levels U-net. Synthetic images are especially relevant for diffraction compensation: they provide realistic and diffraction free dataset. The latter one cannot be obtain experimentally. We show that processed images exhibit higher are clearer disparity that raw images (Fig. 2), which will be helpful for other processing like depth estimation.

![Disparity Maps](image2)

**Fig. 2:** left: disparity on raw image (with diffraction), right: disparity on processed images

Depth estimation can be done using conventional block-matching algorithm, or using CNN. We re-implemented already published DU2Net CNN architecture and show that large training set is mandatory to setup such network [2].

Perspectives
Complementary studies on dedicated processing for quad-pixel will be done combining conventional processing like block-matching and CNN based processing. A quad-pixel image sensor demonstrator is under fabrication. Images taken with this demonstrator will relevantly complete the synthetic dataset.

RELATED PUBLICATIONS:
Parasitic Coupling in 3D Sequential Integration: The Example of a Two-Layer 3D Pixel

RESEARCH TOPIC:
3D sequential integration, image sensors, 3D pixels, 3DSI, monolithic 3D, M3D, coupling, parasitic capacitances

AUTHORS:
Petros Sideris, Arnaud Peizerat, Perrine Batude (DCOS), Gilles Sicard and Christoforos Theodorou

Context and Challenges
In the field of 3D Integration technologies, an important driving application is the CMOS Image Sensor (CIS), as it requires the heterogeneous integration of different system parts. The example presented in this work is a 2-layer 3D pixel, which includes a photon-to-electron converter (photodiode), an analog readout part, an A/D conversion and a digital image processing. CIS is an ideal candidate for studying coupling effects in 3D integration technologies, as it is highly sensitive to noise (dynamic) and mismatch (static) variations.

Main Results
In order to carry out our study, the simulation structure depicted in Fig. 2 was considered. By varying TG gate voltage bias within its normal operation limits (0–2.5 V), we observe a shift of the ID–VG characteristics for the top devices, as shown in Fig. 3.

Concerning the example of the two-layer 3DSI pixel studied in this work, in a typical rolling readout operation, sequential pixel activation implies that there is no probability for a readout error due to TG coupling. Furthermore, the Correlated Double Sampling (CDS) stage that exists commonly after the readout circuit eliminates possible readout errors. Therefore, despite strong electrical coupling and high threshold voltage shifts (~100 mV) for top-tier devices, we demonstrated that a sequentially integrated 3D CIS can have an inherent immunity to inter-tier coupling, with zero readout errors.

Perspectives
The direct stacking of the readout tier upon the photodiode area is safe without the necessity for electrical isolation in a 3DSI CIS. However, an inter-tier Ground Plane is mandatory in cases where sensitive blocks are considered to be placed above the photodiode area, such as in-pixel frame memory for which the leakage current is a critical parameter.

RELATED PUBLICATIONS:
A 1Mb mixed-precision quantized encoder for image classification and patch-based compression

RESEARCH TOPIC:
Embedded deep learning, convolutional neural networks, model quantization, image compression

This work demonstrates that an ASIC Neural Network accelerator can be compatible with various image processing tasks, classification and compression, while requiring a very limited hardware. The key component is a reconfigurable, mixed-precision (3b/2b/1b) encoder that takes advantage of proper weight and activation quantizations combined with convolutional layer structural pruning to lower hardware-related constraints (memory and computing). We introduce a novel adaptive symmetric quantization for ternary/quinary weights training along with the hardware-friendly Bit-Shift Normalization. At 1Mb model size, the classification accuracy reaches 87.5% on CIFAR-10. Besides, this quantized encoder can also be used to compress image patch-by-patch while the reconstruction can be performed remotely, by a dedicated full-frame decoder. This solution allows an end-to-end compression without any block artifacts, outperforming patch-based state-of-the-art techniques.

Context and Challenges
As Convolutional Neural Networks (CNNs) has achieved remarkable success on various applications, pushing CNN inference to the edge devices is ubiquitous. For this purpose, one option is to develop generic hardware platforms dedicated to multi-purpose DNNs while achieving high TOPS/W as the target efficiency metric. An alternative design approach is more related to Application-Specific Integrated Circuits (ASICs) that are dedicated to a certain task, requiring hardware-algorithm co-design to meet a tiny hardware budget (e.g., memory, computational capability). It clearly motivates the use of CNN compression techniques [1], including efficient model design, network quantization and pruning, which increase the hardware efficiency but sacrifice algorithmic overall performance.

Main Results
This work [2] tackles the aforementioned issues of ASIC design from the algorithmic point of view, by proposing a mixed-precision encoder that can be applied for both embedded image classification and patch-based compression, while improving hardware efficiency/algorithmic performance compromises. Fig. 1 depicts an overview of the proposed framework, in which the key element is a weight-reconfigurable encoder with 3b/2b/1b weights, bit-shift normalization and Half-Wave Most-Significant-Bit (HWMSB) activation with favorable hardware compatibility. We propose PURENET decoder for the reconstruction of image from patch-based measurements.

The efficiency of our framework on image classification and patch-based compression tasks is illustrated by Table 1 (improved model size/BOPs vs. accuracy compromise) and on Fig. 2 (reconstructed image without block artifact).

<table>
<thead>
<tr>
<th></th>
<th>Bankman et al.</th>
<th>Kim et al.</th>
<th>Cai et al.</th>
<th>This work</th>
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<td>Weight precision</td>
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<td>86.05</td>
<td>88.80</td>
<td>90.03</td>
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</tbody>
</table>

Table 1. Comparison of low-precision CNN processors (CIFAR-10 image classification task).

Table 2: Example of image reconstruction from patch-based binary measurements, at the bit-rate of 0.25bpp. Left: original image. Right: reconstructed image (PSNR: 22.71dB).

Perspectives
The results demonstrates the possibility of improving the application-versatility of ASIC designs while reaching better efficiency/algorithm trade-offs. Further works may seek an extension to video inference with the quantization of recurrent layers (e.g., LSTM). Another option is to applying multi-task learning to alleviate the need of weight-reconfigurability.

RELATED PUBLICATIONS:
Study of an integrated pre-processing architecture for smart-imaging-systems, in the context of low power computer vision and embedded object detection

RESEARCH TOPIC:
Smart Image Sensors, Artificial Intelligence, Object Recognition.

AUTHORS:
Luis Cubero Montealegre, Arnaud Peizerat, Dominique Morche (DSYS), Gilles Sicard

Embedded Computer vision, as many real application scenarios of artificial intelligence, is facing hardware and power constraints with the rising of edge computing applications. In this work, we have studied, and preliminary characterized (with behavioral simulations and on-paper electronic-models) the use of a ROI-proposals structure, based on Edge-Boxes algorithm, for hardware-constrained devices, in the context of integrated-IC smart-image-sensing architectures. Our motivation was to replace the typically used “sliding-window-approach” in embedded smart-image-systems scenarios. Thanks to a custom simulation-based framework developed during this thesis, we are able to compare detection architectures (including event-based one) and able to show the efficiency of such architecture in an embedded context with strong constraints on power consumption and available hardware.

Context and Challenges
The object detection problem (Fig. 1a), consisting in finding different objects of specific classes (types) in an image, turns out to be quite complicated to embed near the image sensor. Indeed, two complex tasks are required: multi-scale localization and multi-class classification to identify bounding boxes that perfectly enclose each object, whatever its size, and to label the type of the detected object. Today these tasks are mainly often performed on general-purpose desktop machines. Nevertheless, attractive applications like autonomous-driving, augmented reality or video surveillance are urging the need for low-power, low-latency and compact low power devices. The state of the art has approached this challenge by optimizing specific sections of the complete processing-pipeline for a comparable object detection performance. A typical example in the last decade corresponds to minimizing the computing precision, hence the power, to a minimal value. Diminishing the bit-depth or image size has then been studied, while implementing pre-processing steps that increase robustness against the loss in bit and image resolution. An algorithm that doesn’t require that kind of pre-processing stage to be programmable is obviously desirable in order to simplify its implementation (e.g. no memory access to learned weights). Another strategy has been to reduce power due to I/O communications amongst different chips or devices thanks to a more exhaustive integration of specialized circuitry and thanks to more efficient memory accesses and mathematical operations.

Main Results
In that context of near-sensor computing, this work points towards a more energy efficient detection pipeline (Fig. 1b). We target several specific key aspects. First, we try to assess if a dedicated-class-agnostic region proposal algorithm, based on pre-processed low-level features, (replacing typical sliding window approach) for object localization. Then, we propose a pipeline that takes into account near image sensor features extraction for Region Proposals with an algorithm called EdgeBoxes. Second, we try to assess an optimal type of pre-processing that would allow extracting low level features (oriented gradients), and give the best trade-off between power consumption, hardware complexity and object detection performance.

Fig. 1: a) Basic work context. b) Object Detection Pipeline

Our methodology relies on behavioral simulations carried out thanks to a custom framework written in Python and C++ code. We propose a hierarchical model of different image acquisition and processing techniques, and we study their performance through specific metrics related to runtime, memory usage, hardware complexity, I/O data-rate, localization performance and classification performance.

We provide comparison between our novel object detection pipeline and the state of the art and we obtain several benchmarks giving guidance to choose one or another architecture depending on the specific needs. We conclude by stating which one would give, from our perspective, the best trade-offs in term of power consumption and recognition capability.

Perspectives
The next step will be the first silicon implementation of the proposed architecture. Upgrades have to be made on the electronic implementation of Edge Boxes algorithm.

The custom framework provides very interesting and original feedbacks on the studied architecture. It needs to be improved to become more user friendly.

RELATED PUBLICATIONS:
• Noise in perovskite Gamma-ray detectors better understood
• Defects in CZT Gamma detectors are simulated efficiently
• X-ray "colour" imagers can have high spatial and energy resolutions, simultaneously
Noise spectroscopy study of methylammonium lead tribromide single-crystal detectors: gamma-ray spectroscopy applications

RESEARCH TOPIC:
Gamma-ray detectors, noise spectroscopy, perovskites

AUTHORS:
E. Gros-Daillon, O. Baussens, G. Montémont, L. Hirsch\(^1\), JM Verilhac\(^2\)

Metal halide perovskites have been studied since 2016 for gamma-ray spectroscopy applications. In this work, we study devices based on methylammonium lead tribromide single crystals as gamma-ray detectors. Their energy resolution is limited by the noise of the detectors. Such noise is multicomponent and a deeper investigation was carried out by measuring the noise power spectral density of devices for different bias voltages. The dominant noise source is found to be the 1/f noise softened by a shallow trap.

**SCIENTIFIC COLLABORATIONS:**
\(^1\) University Bordeaux, IMS-CNRS, UMR 5218, Bordeaux INP, ENSCBP, F33405 Talence, France
\(^2\) University Grenoble Alpes, CEA, LITEN, F38000 Grenoble, France

Context and Challenges
Metal halide perovskites are a new type of semiconductor that has attracted the interest of the gamma-ray radiation detection community for the past few years. The reasons behind this interest are the presence of heavy atoms, such as lead, in their composition, the good charge transport properties (\(\mu\tau_e \approx 10^{-4}\) cm².s⁻¹, \(\mu\tau_h \approx 10^{-2}\) cm².s⁻¹) and the possibility to grow thick single crystals in solution at low temperature.

In this work, we study the noise spectroscopy of methylammonium lead tribromide (MAPbBr\(_3\)) single crystals grown from solution.

**Main Results**
The noise power spectral density (PSD) of two MAPbBr\(_3\) devices was measured using the setup schematized in fig.1. The simplest electrical equivalent circuit model for the device is a resistor in parallel with a capacitance (R\(_{\text{dev}}//C_{\text{dev}}\)).

The noise PSD can be modeled using the algebraic expressions of the theoretical noise sources of the different constitutive elements of the system. The two main sources of noise are the MAPbBr\(_3\) device and the charge preamplifier. The device noise can be broken down into two main components: the shot noise and the flicker noise (1/f noise). The noise of the amplification electronics is mainly related to the components located upstream of the charge preamplifier: the input resistor (Johnson noise) and the input transistor (JFET) valued by the devices capacitance. However, the simulated PSD overestimated the shot noise for mid-range frequencies. This was attributed to the noise softening by the superficial trapping of the charge carriers. Fitting of the experimental data (fig.2) leads to trapping time of 3\(\mu\)s.

**Fig. 2:** Noise spectral density of two devices. Simulation (solid lines) and measurement (dots)

**Perspectives**
The noise power spectral densities of MAPbBr\(_3\) devices and their spectral chain were measured to uncover the main noise sources that limit the energy resolution of gamma-ray photon counting measurements. For non-biased devices, we found that the main noise source is thermal noise from the resistances of the devices. However, when the devices are biased, the noise is dominated by the 1/f noise of the devices at low frequency (<1MHz). To our knowledge, this is the first result that highlights the major contribution of flicker noise in thick hybrid perovskite detectors used for radiation detection. Further research will need to focus on the comprehension of the physical phenomena responsible for this 1/f noise in the devices.

RELATED PUBLICATIONS:
CZT detectors are a common type of gamma detectors for applications as medical imaging or safety due to its interesting properties. Classic simulations assume the crystal perfect. However, structural defects appearing during the crystal growth modify the properties. Moreover dynamic phenomena like polarization can appear. In particular, the electric field inside the detector can be disturbed by bulk charges, generating uncertainty on measurement of incident photon energy and on its position estimated by sub-pixel positioning. Predicting the nature and position of these defects may allow correcting the detectors output values and improving its performances.

The complexity of a simulation considering these non-uniformities is an issue. Hence, we have developed a model allowing electric field modifications and enabling quick observations of the detector’s response modifications vs the electric field. We leveraged GPU to address such computational burden. Indeed, we can afford to consider more complex simulations as the computation time is reduced.

Context and Challenges
The wide range of defects in real CZT detectors prevent the development of large volume detectors. Their effects on the physics of the detector modify the output signals and decrease the performances of the device.

3D Simulations of CZT detectors allow observing the behavior of these defects on the properties of the detector, as the electric field. Point-type, planar or spherical defects can be implemented in a geometrical way to better understand their impact.

However introducing these defects to obtain a realistic simulation requires a strong computational power. It is why the use of Graphics Processing Units (GPU) is essential. It enables to parallelize the simulations of millions of photon interactions in the detector, and to speed up the calculations.

Main Results
Four types of situations have been introduced: a distribution of small point defects, a loaded planar defect, a high conductivity spherical defect and an intense X-ray irradiation over the cathode.

Each type of defect depicts a different impact on the electric field of the detector, curving or deflecting it. The Charge Induction Efficiency (CIE) is also studied, and it has been seen that the presence of defects often leads to a leak of charge collection over the anode, due to the deviation or trapping caused by the electric field variations.

Perspectives
This work is the first step of the development of an analysis tool, which could be used to characterize the impact of real defects using modelling for a better understanding of the electric field inside CZT detectors. This tool would allow to calibrate the detectors to take into account the position and type of defects in the crystal volume to correct the output signal.

Fig. 1: Electric field lines in the detector with spherical defect.

Fig. 2: 2D CIE of a detector with spherical defect.

RELATED PUBLICATIONS:
ColorCT: Design of a Photon Counting Detector with Optimized Spectral Response for Computed Tomography

RESEARCH TOPIC:
X-ray detectors, Medical imaging, Computed tomography

AUTHORS:

The future medical spectral CT scanner systems for X-ray colour imaging require performant energy resolved Photon Counting Detectors (PCDs) capable of providing a good energy discrimination under very high X-ray fluxes. The ColorCT project aims to develop a PCD demonstrator with optimized performance to improve the quality of diagnosis. We present the results of a simulation study to design the pixel and test new approaches to improve the spectral response. We show that it is possible to design a detector with a 200-µm pitch with optimized spectral performance over the entire flux range of X-ray tomography, thanks to advanced correction algorithms implemented inside the pixel.

Context and Challenges
Spectral Computed Tomography (CT) is a technological breakthrough that will improve the quality of medical diagnosis while reducing patient dose and increasing spatial resolution. Above all, energy information opens the way to quantitative and functional imaging.

The objective of the ColorCT project is to develop and test a new generation of Photon Counting Detector for spectral CT integrating advanced processing in order to improve the spectral response at very high X-ray flux. The main challenge is to obtain the best spectral performance over a wide range of X-ray fluxes, in order to ensure good separation of the different biological tissues and of the contrast products injected into the patient. In the end, this improvement in performance should make it possible to improve the quality of diagnosis, while reducing the patient dose.

Main Results
We use a Monte-Carlo simulation tool based on a semi-empirical detector model to estimate the spectral response of the PCD [1]. Comparison with the response of a 4x4 pixel matrix prototype shows an excellent agreement of the simulation results for typical CT X-ray spectra. This tool allowed us test several pixel designs.

Figure 1 shows count rate and the photoelectric efficiency as a function of the incident flux of X-rays for a 200-µm pitch. An original fast front-end RTIA amplifier with 10 ns peaking time [2] and an advanced Pile-Up Recovery (PUR) algorithm [3] greatly reduce the count rate losses over the entire X-ray flux range of CT applications. An optimized Charge Summing Correction (CSC) algorithm detects charge sharing in order to eliminate double counting and correct the signal amplitude. This correction improves the photo-peak efficiency, which measures the ability of the detector to measure X-rays in the correct energy channel. Complementary simulations have demonstrated that this criterion is correlated with the ability to discriminate between the different biological tissues and contrast products, thus inducing a true benefit for the diagnosis.

Fig. 1: Effect of fast front-end amplifier (RTIA), Pile-up Recovery (PUR) and Charge Summing Correction (CSC) on count rate and photo-peak efficiency performances, for a 200-µm pixel pitch.

Perspectives
A preliminary study has demonstrated that it is possible to integrate the entire processing chain into each single pixel with a 200-µm pitch of the ASIC with a consumption of less than 3 mW/mm², using 65 nm CMOS technology.

These promising results led us to start the ColorCT project, with the aim of designing, manufacturing and characterizing an operational demonstrator of an imager with optimized performance for spectral tomography.

RELATED PUBLICATIONS:
Si photonic platform enables quantum communications and computing

- III-V-on-Si semiconductor lasers spike as neurons
- Perfectly vertical grating fiber couplers "automatically" designed and fabricated by immersion lithography
- Fiber grating couplers operate via the chip backside with low loss
- Mass reflow bonding automatically aligns Si photonic chips to better than 1 µm

(and more in the "Lidars" chapter)
Towards an integrated quantum photonics platform for quantum communications and computing

RESEARCH TOPIC:
Integrated quantum photonics, silicon photonics, single photon sources, single photon detectors

AUTHORS:

Silicon photonics is a very attractive technology platform to meet the requirements of future widespread deployment of emerging applications such as perfectly secure quantum communications and quantum computing. Specific components are required to generate, manipulate, encode and detect single photons which will be used as photonic qubits. For this purpose, we have developed several key functions on 200 mm SOI wafers using CMOS-compatible fabrication technology: ultra low-loss propagation waveguides (0.5-1.5 dB/cm), sources of photon pairs with MHz generation rate and waveguide-integrated superconducting nanowires with improved critical temperature for single photon detection.

SCIENTIFIC COLLABORATIONS: 1 CEA-IRIG, 2 University of Pavia (Italy)

Context and Challenges
Single photons, which feature excellent robustness against decoherence effects, are ideal qubits for emerging applications such as perfectly secure quantum communications and quantum computing. Such quantum information applications require a scalable, compact and low-cost technology for future widespread deployment. Silicon photonics is a very attractive technology platform for this purpose, to implement several key functionalities such as photonic qubit generation, coherent manipulation, encoding and detection.

Main Results
Minimizing propagation losses on-chip is one of the key requirements for building quantum photonics components and circuits. We have developed a specific post-etching of silicon waveguides to reduce propagation losses down to the record values of 1.5 and 0.5 dB/cm for strip and rib waveguides respectively [1].

For the generation of photonic qubits, we have developed time-energy entangled sources of photon pairs by exploiting the non-linear four-wave mixing effect in high quality factor ring resonators (loaded Q factor of 3.10^5) to generate time-energy entangled photon pairs with a rate of a few MHz [2] (fig. 1).

For the detection of photonic qubits, we have developed an entirely CMOS-compatible fabrication technology of NbN nanowires (5 nm thickness and 70-100 nm width) with improved critical temperature (thanks to the use of an AlN buffer layer) [2, 3] and excellent homogeneity of electrical resistance across 200 mm wafers (fig. 2).

Fig. 2: (a) Improvement of NbN critical temperature; (b) SEM picture of Si waveguide-integrated NbN/AlN nanowire.

Perspectives
The ultimate perspective is to provide all the key resources for qubit generation, manipulation, encoding and detection integrated on a single platform (fig. 3).

For this purpose, we have initiated the development of high-speed, low-loss and cryo-compatible phase shifters based on the hybrid integration of LNBO3 material on the Si platform.
Design of an integrated III-V on silicon semiconductor laser for spiking neural networks

RESEARCH TOPIC:
Spiking Neural Networks, Artificial intelligence, Lasers and Silicon Photonics

AUTHORS:
B. Charbonnier, K. Mekemeza Ona, K. Hassan

Photonics is seen as a promising solution to implement next generation spiking neural networks leading to reduced energy consumption per inference as weighted sums can be realized in the optics domain in a quasi-lossless manner (coherent interferences). One further step to maximize the benefits of such developments is the implementation of analogue photonics neurons, thus ensuring an end-to-end high computational rate (>GHz). Spiking (Q-switched) lasers exhibit a behavior that is very similar to that of Leaky Integrate and Fire (LIF) neurons and III-V on SOI integration developed in Leti allows such lasers to be densely integrated into silicon photonics circuits. We have designed a laser architecture suitable for fulfill the LIF neuron role. This design is being fabricated and a full prototype circuit is expected to be designed following the individual laser tests.

Context and Challenges
As artificial intelligence (AI) is gaining importance into our daily lives, data generation, analysis, storage and transport are becoming omnipresent requirements and thus new paradigms to try and reduce the energy consumed while manipulating what is often called the data deluge must be found. The idea to deploy AI at the edge of the network rather than in the core was conceived exactly for this reason: if data is analyzed at the edge, then there is no need to transfer it to the core (where historically the computing power resides) for analysis and the resulting decision is available to the user without further latency. Microsoft states that at least 16Gbps must be analyzed real time for an autonomous car to drive. However, the training and operation of a large digital AI circuits leads to an extremely high power consumption which is still acceptable (although not desirable) for the core but is clearly way above edge device capabilities. Low power per inference circuits using analogue synaptic networks rather than digital ones (also called computing accelerators) have been successfully implemented in CMOS, leading to orders of magnitude power savings (example : NVIDIA GPU). Recently, even lower energy consumption synaptic circuits have been demonstrated using silicon photonics (LightMatter for instance). Further energy savings are possible because photonic synapses using light interferences are "lossless" by nature and although there is an initial energy cost to converting the data to the optical domain, the global synaptic operation remains power efficient [1]. However, if the use of photonic analogue synaptic networks is clearly demonstrated now both technically and commercially, the neurons are still digital in general and as a result, the full benefits of a photonic implementation cannot be achieved: multiple optoelectronic (OE) and electro-optic (EO) conversions are needed as well and digital to/from analogue conversions (DAC and ADC). Additional energy efficiency could be unlocked if photonic neurons could be used.

Here we present our concept of a photonic spiking neuron using a Q-switch laser integrated in a Silicon Photonics (SiPho) platform for future low power neuromorphic processors.

Main Results
Continuous wave (CW) Laser integration in SiPho by Leti have been reported in several papers and shows a high potential for dense active photonic circuits as required for photonic spiking neural networks. The architecture of the laser however has to be adapted for pulsing operation, a necessary step to obtain a behavior comparable to that of a Leaky Integrate and Fire (LIF) neuron. In order to achieve Q-switch operation, part of the gain section of the laser has to be electrically insulated from the rest to produce a saturable absorber (SA) in the laser cavity. As the SA needs to be driven in reverse, contrary to the remainder of the gain section (direct biasing), the electrical insulation between the two contacts must be high (MD) without compromising the optical propagation. A complete study of the geometry of the laser has been performed in [2-3] and has led to prototyping runs currently being fabricated.

In parallel, the training of deep spiking neural networks (SNN) has been studied. Historically, only small SNN have been used so far because their training and simulation is relatively hard to achieve. However a recent proposal for an efficient backpropagation algorithm for LIF based SNN (T. Wunderlich) has led us to develop our own LIF model (very close to a q-switch laser) and backpropagation algorithm, suitable for a full photonic implementation.

Perspectives
When the fabricated laser prototypes will have been tested and models extracted, a full LIF-laser-neuron based SNN will be designed and fabricated in order to prove the concept. The novel photonics adapted backpropagation algorithm will be tested in real life for SNN supervised training.

RELATED PUBLICATIONS:
Vertical grating fiber coupler designed by the inverse design method and fabricated by immersion lithography

RESEARCH TOPIC:
Silicon Photonics

AUTHORS:
Quentin Wilmart, Stéphanie Garcia, Bertrand Szelag, Estelle Guyez (DPFT), Sean Hooten¹, Thomas Van Vaerenbergh¹

Context and Challenges
The grating coupler is a major component of photonic integrated circuits (PIC). It enables the optical coupling of the PIC and a fiber with relatively low loss and good alignment tolerances. In particular, grating couplers are key for wafer level testing of circuits and devices during the development and prototyping phases. Grating couplers are traditionally designed to couple light to slightly tilted fibers in order to avoid large back reflections arising when the scattering angle is perpendicular to the grating plane. However, complex grating designs can help reducing the back reflection, making possible the perfectly vertical coupling in practical devices. The complex geometry of low-reflection vertical coupler can be obtained using the inverse design method: the algorithm tries to optimize the device geometry given a targeted optical response. This possibility opens very interesting opportunities in term of optical packaging with simplified connector design and assembly process.

Main Results
Vertical grating couplers are designed using an inverse design procedure based on the adjoint method and following the fabrication constraint of a 60nm minimum feature size. The set of structures referred as design of experiment (DOE) contains 1608 devices, which are first tested using numerical simulation (FDTD). The DOE is then fabricated using the 300mm silicon photonics platform of CEA-Leti. In particular, SOI wafers are patterned using immersion lithography in combination with an optical proximity correction (OPC) algorithm. The silicon layer is partially etched from 300nm to 165nm to define the grating trenches, and the structures are oxide encapsulated and planarized.

The grating couplers, arranged in loop back structures, are optically tested on an automated 300mm probe station with a fiber array. The 6σ repeatability and reproducibility of the setup is estimated to 0.3dB. The full DOE is first characterized on 5 dies of a wafer. Then, the best device is tested on the full wafer (67 dies). The device of record shows (median values) insertion losses of 1.8dB, a -1dB bandwidth of 20.5nm and a reflectivity of -16.5dB. These values corresponds to the state-of-the-art for vertical grating couplers.

Fig. 1: (a) Vertical grating coupler and optical fiber. (b) Optical picture of the loop-back test structure. (c) and (d) Wafer level map of insertion losses and reflectivity respectively, for the device of record.

Perspectives
Thanks to the combination of the inverse design method and an advanced silicon photonic fabrication line, we demonstrate a state-of-the-art vertical grating coupler, which might simplify connector designs for optical I/O. Further improvement of the vertical coupler are expected using the multilayer Si/SiN photonic platform developed at CEA-Leti.

RELATED PUBLICATIONS:
Fiber grating couplers for optical access via the chip backside

RESEARCH TOPIC:
Silicon photonics, Fiber coupling, diffraction grating, Photonic integrated circuits.

AUTHORS:
David Fowler, Quentin Wilmart, Stéphanie Garcia, Ségolène Olivier, Bertrand Szelag.

For the majority of packaging schemes in silicon photonics, out-of-plane optical access to the waveguide layer is achieved via the chip frontside, away from the substrate. As such, fiber grating couplers have generally been optimized with this in mind. In this work, we present two strategies for designing a fiber grating coupler for coupling to optical fibers placed on the backside of the chip, without the need of superposed reflective layers. An all silicon O-band grating coupler is designed, fabricated and measured with a peak coupling efficiency to a single mode fiber placed on the backside of the chip of -2.8dB and a -1dB bandwidth of ~40nm. In a second approach, a hybrid silicon nitride/silicon O-band grating coupler is measured in the same configuration with a peak coupling efficiency of -3.2dB and a -1dB bandwidth of ~60nm.

Context and Challenges
Using CMOS compatible manufacturing processes allows access to large volume and low cost fabrication of on-chip photonic transceivers [1–3]. Over the last two decades, SOI based platforms have been developed, offering high performance optical components such as high-bandwidth modulators [4], (de-)multiplexers [2], photodiodes [5] and integrated lasers [6]. Due to the indirect bandgap of Si, the latter device requires the integration of an InP-stack onto the Si-wafer in order to fabricate a Hybrid III-V/Si laser. The thickness of the InP stack of several micrometers necessitates a significantly modified back end of line (BEOL) process [7] to create metallic connections to the active photonic components. These modifications can introduce constraints with regard to the integration of other functions such as RF lines for travelling wave modulators and the incorporation of additional waveguiding layers.

Another means of creating a Hybrid III-V/Si device is to access the waveguide layer from the backside of the waveguide (see Fig. 1). Following a standard BEOL process, the wafer can be inverted and the substrate and BOX layer removed [8]. This has the advantage of an undisturbed BEOL process, but optical access to the photonic layers must now be achieved from below the waveguide rather than above it, as for a traditional configuration.

In this work, we present the design and measured performance of all silicon and hybrid SiN-Si diffraction gratings specifically designed for coupling waveguided light to a fiber placed on the backside of the chip, without the need of a reflective layer in the BEOL.

Main Results
Two approaches to designing and fabricating diffraction gratings to couple waveguided light to a fiber placed on the chip backside without the use of superposed reflective layers have been described and tested experimentally.

RELATED PUBLICATIONS:
Self-assembly and mass reflow of copper bumps for flip-chip hybridization in photonic applications

**RESEARCH TOPIC:**
3D Integration and packaging, Flip chip, Photonic assembly

**AUTHORS:**

The 3D integration of photonic devices to provide heterogeneous optical/electrical systems implies the use of Tin Silver based flip chip technologies. These technologies are known for quite a long time but photonic brings additional requirements and constrains. The quality of the beam transport between the different components of the assembled system is strongly depending on the accuracy of the alignment between them. At least, the frequent presence of structures (as microlenses) on all faces of the components require a particular care in the down force applied during hybridization. For these reasons, the conventional thermo-compression assembly appears limited and the accuracy of actual industrial flip chip bonders is far from the requirements. A specific assembly method, named "mass reflow bonding" was developed CEA Leti DOPT/LAIP and has shown a self-alignment behavior leading to <1µm alignment.

**Context and Challenges**
Flip chip assembly of SnAg based microbump is the reference process in advanced 3D heterogeneous integration and packaging. The introduction of photonic devices in this type of integration induces new requirements in the accuracy of alignment between the hybridized chips. The typical alignment accuracy of an industrial flip chip bonder is in the range of 5µm while the alignment of photonic components, to allow the proper optical performances of the signal, are tending to require 1µm range accuracy which is far below the normal specification.

A specific assembly methodology, developed in the past years in the packaging lab of the DOPT and based on a self-alignment of structures during liquid phase of the bonding process was applied, in the field of the H2020 European project PIXAPP, to enable a 1µm accurate alignment. The Goal of this work is to integrate a micro-lenses array on the surface of an emitting PIC to enable "pluggable" fiber connectors.

**Main Results**
The bottom die, a photonic IC, integrates 25µm diameter microbumps composed of a Cu/Ni/SnAg stack deposited by electroplating. The signal is brought through grating couplers and waveguides from the fiber insertion area to the extraction area where the microlenses are to be positioned by flip-chip. These microlenses are issued from a silica wafer on which they are designed on one side. UBM pads made of a Cu/Ni/Au stack and presenting same dimensions as the µbumps are designed on the opposite side. Figure 1 summarizes both top and bottom dies and the final assembly.

The process consists, in a first preparation of the SnAg surface to removed the native oxide. This phase is critical as the rest of the process will induce no down force to promote the contact. When both dies are aligned by the flip chip bonder, contact is made with a minimum down force to avoid lens degradation. Full wafer can then be populated before the collective reflow, at 250°C enables the SnAg liquid phase formation, the wetting on the UBM surface and the NiSn Intermetallic compound formation. During this phase, capillary forces take place and, as shown on fig.2, repositions the µbump on the UBM, leading solidification to a perfectly aligned connection. During this study, repeatable alignments better than 1µm were obtain while the flip chip bonder specification is 5µm and a specific Qtime evaluation showed that this behavior was taking place during more than 24h after surface preparation showing the ability to fully populate 200 or even 300 mm wafers.

Mechanical tests (Shear tests) showed good reliability of the obtained structure and further optical tests performed on the structurer showed excellent results.

**Perspectives**
Mass reflow process is a reference process for flip chip mass volume production and appears very attractive for photonic applications as no constrains are applied to any faces of the assembly thus no degradation. We have shown that alignment far below the tool specifications and compatible with photonic requirements can be obtained. The next phase of the work will be to implement this process as a standard one in the next projects DOPT will lead in photonic packaging.

**RELATED PUBLICATIONS:**
• Optomechanics enhances optical sensing
• In-situ doping improves mid-IR emission of GeSn LEDs
• Mach-Zehnder silicon interferometers sense and classify odors
• Multispectral infrared imaging identifies microbial colonies
A lensed fiber bragg grating-based membrane-in-the-middle optomechanical cavity

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

AUTHORS:
Joris Baraillon, Boris Taurel, Pierre Labeye, Laurent Duraffourg (DCOS)

Optomechanical systems benefit from the coupling between an optical field and mechanical vibrations. Fiber-based devices are well suited to easily benefit from this interaction. After characterizing a fiber-based cavity, CEA-Leti works on an integrated silicon nitride membrane in a high quality factor ($10^6$–$10^7$) Fabry–-Perot cavity. The Pound–Drever–Hall technique used to stabilize the laser frequency on the optical resonance frequency allowed us to reduce the low frequency noise down to $4 \text{kHz/Hz}^{1/2}$. This methodology allowed for the characterization of the optical and optomechanical properties of this stabilized system, using various membrane geometries, with corresponding resonance frequencies in the range of several hundred of kHz. The excellent long-term stability is illustrated by continuous measurements of the thermomechanical noise spectrum over several days, with the laser source maintained at optical resonance. This major result makes this system an ideal candidate for optomechanical sensing.

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. In order to validate this concept, we studied a fiber based optical cavity with a silicon nitride membrane in order to adapt stabilization techniques such as the Pound–Drever–Hall technique, measure the optomechanical characteristics of the integrated membrane and assess the performances that could be obtained when used as a trace gas sensor.

Perspectives
This experimental work led to signal to noise ration improvements of almost three decades (see figure) at low frequency, coupled with an exceptional stability of the device. These results allowed us to evaluate the sensitivity of a CO2 gas sensor based on this approach to approximately 50 ppb comparable to state of the art CO2 gas sensors.

Fig. 1: Experimental setup (top) and signal to noise ratio enhancement by using Pound-Drever-Hall technique (down).

RELATED PUBLICATIONS:
In-situ doped GeSn light emitting diodes for the mid-infrared

RESEARCH TOPIC:
Optoelectronics, Group-IV semiconductors, GeSn, LEDs, MIR emitters, gas sensor.

Authors:
L. Casiez, C. Cardoux, M. Frauenrath (DPFT), R. Pellerin (DPFT), N. Pauc, V. Calvo, N. Coudurier (DPFT), P. Rodriguez (DPFT), J.-M. Hartmann (DPFT), A. Chelnokov, V. Reboud.

Thanks to their direct band gaps, (Si)GeSn all-group-IV alloys are promising candidates for light sources, photodetectors and modulators monolithically integrated onto a CMOS-compatible mid-infrared photonics platform. Several research teams have demonstrated optically pumped GeSn lasers, and, more recently, an electrically pumped GeSn laser operating at low temperature. In this framework, in-situ n-type doping of GeSn with Ge2H6, SnCl4 and PH3 was investigated at CEA to fabricate LEDs on Ge strain-relaxed buffers, themselves on Si(001) substrates. Electrically active carrier concentrations up to $6.9 \times 10^{19}$ cm$^{-3}$ were achieved in GeSn:P with smooth surfaces obtained. Our aim was to replace the in-situ phosphorous doped pure Ge layers used in previous LEDs pin structures with GeSn:P injection layers. A 240 nm GeSn:P layer at $3 \times 10^{19}$ cm$^{-3}$ was therefore grown on a direct band gap Ge0.87Sn0.13 layer to replace the top Ge:P layer. An enhancement of the electroluminescence was achieved thanks to a better current spreading and, possibly, to a better band alignment of the GeSn:P layer with the Ge0.87Sn0.13 emitting layer just below.

**Context and Challenges**

Silicon photonics in the near-Intra-Red, up to 1.6 µm, is already one of key technologies in optical data communications. However, silicon photonics does not yet address a large number 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. Markets for such analysis are huge and constantly growing, with a strong push towards 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, as Ge can be turned into a direct bandgap semiconductor by alloying it with more than 8% of Sn, typically. In this framework, we succeeded in growing in-situ phosphorous doped GeSn layers on top of Ge0.87Sn0.13 light emitting devices (LEDs) on 200 mm Ge Strain-Relaxed Buffer (SRBs). Those LEDs have better light emission properties than that with Ge:P contact layers.

**Main Results**

The in-situ doping of GeSn alloys was investigated in Reduced-Pressure Chemical Vapor Deposition (RP-CVD) on p-type doped Ge SRBs, themselves on 200 mm Si (001) wafers. Our investigations, carried out at 349 °C, 100 Torr, gave new insights into the growth mechanisms of intrinsic and doped GeSn with around 6% of Sn. Atomic phosphorus concentrations as high as $3.9 \times 10^{19}$ cm$^{-3}$ were obtained in GeSn:P with electrically active carrier concentrations as high as $6.9 \times 10^{19}$ cm$^{-3}$. The discrepancy was likely due to the presence of large amounts of electrically inactive Sn$\text{P}_x$-V complexes [M. Frauenrath et al., ECS J. Solid State Sci. Technol. 10, 085006 (2021)]. Circular mesa-like LED were then fabricated from the 200 nm grown stack (Figure 1a) using conventional lithographic steps described in [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 or GeSn injection layer. Finally, 20 nm of Ti and 180 nm of Au were deposited by evaporation on the NiPt/TIN contacts. Thermal stability of NiGeSn was further increased using pre-amorphization by implantation [2]. The electroluminescence of GeSn LEDs was investigated at room temperature thanks to an optical set-up with a FTIR spectrometer. The integrated signal was multiplied by a factor of 2 for the Ge$_{0.87}$Sn$_{0.13}$ LED thanks to the use of a 240 nm thick GeSn:P layer instead of a 50 nm thick Ge:P layer (Figure 1b). This enhancement was attributed to a better current spreading in the in-situ doped GeSn layer and possibly to a better band alignment at room temperature between the in-situ doped GeSn layer and the active Ge$_{0.87}$Sn$_{0.13}$ layer.

![Figure 1](image1.png)

Figure 1: a/ Ge$_{0.87}$Sn$_{0.13}$ LED stack epitaxied on a Ge-buffered 200 mm Si wafer. b/ Electroluminescence of a Ge$_{0.87}$Sn$_{0.13}$ LED emitting at room temperature with GeSn:P (red) or Ge:P (blue) injection layers. Inset: Cross-section schematics of the Ge$_{0.87}$Sn$_{0.13}$ LED with the GeSn:P top layer.

**Perspectives**

Our results show the feasibility of growing thick in-situ doped GeSn layers to improve current spreading and move away electrical contacts from the active zone for laser applications. GeSn:P LED emission have been significantly improved compared to that of Ge:P LEDs. GeSn alloys are promising light sources for gas sensing. Investigations are underway to further increase light extraction from LEDs for an implementation in gas-sensing platforms.

Related Publications:
A Silicon photonic olfactory sensor

RESEARCH TOPIC:
Silicon photonics, olfactory sensors, Mach-Zehnder Interferometers

Odor sensing could have a strong impact on our daily life, from personal well-being for those suffering from anosmia, to environmental concerns on air quality or food spoilage. Quality control based on odor analysis is also critical for the chemical and food industries. Yet, miniaturized, robust and affordable olfactory sensors keep missing. In 2018, the CEA and Aryballe demonstrated the first universal optical nose based on surface plasmon resonance imaging. In 2019, we presented preliminary results of silicon photonics for this application [1]. Here, we present the first silicon photonic olfactory sensor. Based on an array of 64 Mach-Zehnder Interferometers (MZI), the sensor can analyze odors in air in the ppm range [2]. Its ability to detect and classify odors is demonstrated by a case study on four different samples of vanilla odors [3].

SCIENTIFIC COLLABORATIONS: Aryballe

Context and Challenges
Cameras capture images, microphones capture sounds, lidars capture distances, but capturing odors remain a challenge. Gas analysers, such as gas chromatography coupled to mass spectroscopy, can find which Volatile Organic Compound (VOC) an odor is made of. Knowing the composition of a mixture does not directly gives the odor that one would smell. In contrast, an electronic nose (and now a photonic nose) does not try to identify individual VOC but directly records the global signal an odor generates on an array of sensors with various physico-chemical properties. Silicon photonics offers a mature technology platform to build such a sensor array while micro-drop dispensing allows to biofunctionalize each sensor in order to obtain a rich, multiplexed and specific response.

Main Results
Since 2018, we have been developing a mature silicon photonic platform based on silicon nitride (Si3N4) waveguides operating in the 800-900 nm wavelength range. The waveguides can be both cladded in SiO2 for optical routing and exposed to the air for sensing. A very thin layer of SiO2 is deposited on the sensing waveguides to allow an easy silanisation and biofunctionalization. The oxide cladding etch and thin oxide deposition have been optimized to minimize additional losses compared to bare waveguides before cladding disposition (Fig. 1). Thus, Mach-Zehnder Interferometers (MZI) with a length of 4 mm exhibit extinction ratio up to 18 dB over the 840-860 wavelength range.

Photonics dies with a sensor array of 64 MZI have been designed and manufactured both at CEA-Leti and in a commercial foundry. They are at the heart of the NeOse Advance [4] commercialized by Aryballe in May 2021 (Fig. 2).

Fig. 2: Die miniaturization across 3 generations/years (left). Aryballe’s NeOse Advance released in 2021 (right).

Thanks to CEA-Leti/DTBS surface preparation and Aryballe’s biofunctionalization technique and software suite, even similar odors can be detected and identify in the ppm range (Fig. 3).

Fig. 3: Olfactive signatures of four samples of vanilla aroma (left) and principal component analysis plot of the data showing clustering and discrimination (right).

Perspectives
We are now focusing on on-chip integration of active components in order to miniaturize the system and improve its performances. We are also developing new photonic sensors to make odor analysis faster, more robust and more repeatable. We’d like to thanks the Nanosciences foundation, IRT Nanoelec and BPI France for their support.

Fig. 1: Propagation loss of Si3N4 waveguides at λ=850 nm.

RELATED PUBLICATIONS:
Microbial identification through multispectral infrared imaging of colonies: combining chemical and morphotype analysis within a single wide-field and low-cost system

RESEARCH TOPIC:
Microbial identification, spectroscopy, multispectral Mid-infrared (MIR) imaging

AUTHORS:
Joel Le galudec, Véronique Rebuffel (DTBS), Pierre Marcoux (DTBS), Mathieu Dupoy

The identification of microorganisms in the fields of health, environment and industry is a critical process to determine the microbial species contained in a sample. Currently, there is no technology available to identify microorganisms directly on a Petri dish, with no necessity to collect the colony. Lensless multispectral mid-infrared imaging is a promising diagnosis technology based on transmission imaging of microbial colonies on agar medium. Optical fingerprints were acquired by placing the microbial colonies on the top of a microbolometer array and illuminating them successively with 8 different monochromatic infrared lasers. These fingerprints simultaneously contain both biochemical and morphological information. A database containing 2253 colonies from 8 microbial species was collected. In addition, 3 strains of the same Staphylococcus species (S. epidermidis) were added to test the feasibility of typing with our approach. After classification by Support Vector Machine with a tenfold cross-validation test, 91% of colonies were correctly identified, including colonies belonging to different strains of a same species.

Context and Challenges
The biochemical fingerprint of microorganisms are obtained in the mid-infrared region, between 3 and 12 µm. Spectroscopy FTIR has already been used for several decades as a species- and strain-level identification technique. However, the high absorption of water in this range of wavelengths and the relatively low power of FTIR sources prevent direct acquisition on the culture medium in transmission geometry and require sampling colonies from the Petri dish onto an IR-transparent material prior to analysis. The emergence of Quantum Cascade Lasers (QCLs) with high brightness in the infrared range, opens up new perspectives in discrete frequency infrared spectrometry (DF-IR), such as chemical imaging of human tissues, real-time imaging of microorganisms, or classification of several bacterial species.

Main Results
To avoid the strong water absorption and the transfer of colonies on IR transparent substrate, the bacteria growth is done on an alumina nano porous membrane, which is placed directly on the culture medium. After 24 hours of culture, the membrane is removed from the agar medium, air-dried for 10 minutes, and transferred to infrared multispectral imaging system.

The experimental setup consists in the combination of a set of height lasers and lensless imaging with an uncooled bolometer matrix. The membrane, on the motorized stage, is close to the microbolometer array (<2mm). Each colony is sequentially imaged through the eight wavelengths. A biochemical mapping of the sample is obtained over a wide field of view without labeling. After the image pre-treatment, each single colony is associated with a vector gathering descriptors like colony radius, roundness, or mean intensity at each wavelength. Then the vector is compared to the database and classify through supervised machine learning.

To test the performances of multispectral mid-infrared lensless imaging as an identification technique, a database containing 2253 individuals from 8 microbial species and 3 strains of S. epidermidis was acquired. Support vector machine (SVM) algorithm, machine-learning classification, was finally performed with a tenfold cross-validation test.

The classification leads to the confusion matrix, which is a sort of correlation matrix between the expected species and the detected species. Its diagonal corresponds to the correct identification rate (CIR). The CIR of 91.6 % on average that is promising performance.

Perspectives
A second database of microorganisms, corresponding to real use case, will be carried out with the dedicated prototype.

RELATED PUBLICATIONS:
photonics and microelectronics enable low-cost mass production
Silicon optical phase arrays enable chip-scale LIDAR systems
- p-i-n phase shifters make optical phase arrays more rapid and less power-hungry
- Optical phase arrays are characterized in a dedicated test bench
- Free space 3D FMCW lidar implemented as a scanless imaging system
- Compressing sensing reduces hardware limitations in time-of-flight imaging
Silicon photonics based optical phased arrays for chip-scale LiDAR systems

RESEARCH TOPIC:
Silicon Photonics, Optical Phased Arrays, Solid State Beam Steering, Integrated LiDARs.

The integrated optical phased array (OPA) is a promising solution towards chip-scale LiDAR systems. Thanks to solid-state beam steering, better performing systems could be made while reducing costs thanks to the high-volume manufacturing capability of the microelectronic industry. However, many technical challenges must be addressed prior to the massive deployment of these new sensors. In particular, increasing the number of optical channels of the OPA, from several tens to eventually several thousands, is essential in order to meet system specifications. Targeting the realization of an operational LiDAR system, the CEA LETI is developing high channel count OPA circuits based on silicon photonics.

AUTHORS:

Context and Challenges
Significant effort is currently being directed towards the cost reduction of spatial imaging systems to enable wide scale deployment, notably in the automotive sector. A promising solution consists of using integrated optical phased arrays (OPAs) in order to achieve solid state beam steering, paving the way to a novel generation of high-performance and low-cost LiDAR systems. Since the initial demonstrations of OPAs based on silicon photonics over ten years ago, the maturity of such circuits has steadily increased, but complete systems based on this technology are still in their infancy. With several notable exceptions, the majority of demonstrations have shown OPAs with less than 100 optical channels. However, in order to simultaneously meet system requirements in terms of beam power, field of view (FOV) and beam divergence, it is likely that OPAs with several hundred, if not thousands of optical channels are required.

In cooperation with the CEA startup Steerlight and STM, the LIPS laboratory is addressing the challenges in the development of high channel count OPAs [1] - [4].

Main Results

![Fig. 1: Overview of a 256CH silicon optical phased array.](image)

As shown on figure 1, a 256CH silicon based OPA was fabricated in the LETI cleanroom facility. Using air trenches, the thermo-optical phase modulators can be closely spaced allowing for a compact circuit with reduced power consumption. We developed a unique characterization bench based on a standard 300mm probing station. It allows for wafer level testing of high channel count OPAs, thus avoiding the need of complex packaging steps, which hinders the development of this technology. Significant effort was also deployed in order to simplify the calibration procedure that is required to operate an OPA. By using genetic algorithms together with the phased array theory, this process was reduced to a single and fast step.

As shown on figure 2, using our OPA, a 40° FOV can be mapped with a resolution of 0.2°.

![Fig. 2: Beam scanning over +/-20° with a 0.2° resolution.](image)

Perspectives
On the OPA side, the field of view, scanning speed as well as the beam divergence and power must be increased to meet system specifications. The complex co-integration with other parts of the LiDAR system (laser source, control electronics, receiver…) is also under active study. Furthermore, other OPA applications are envisioned such as free space communication and holographic displays.

RELATED PUBLICATIONS:
Fast optical phased array on a 300-mm silicon platform

RESEARCH TOPIC:
Silicon photonics, Optical Phased Array (OPA), Light Detection And Ranging (LiDAR), Phase modulator

We present an analysis the use of an optical phased array for automotive and handheld device LiDAR systems and preliminary results from a 16 channel silicon optical phased array using p-i-n phase shifters built on a 300-mm industrial platform to reach high-speed operation and low power consumption at a 1.55 𝜇m wavelength. Using 2 𝜇m-spaced grating antennas OPA with theoretical beam steering range of 48°, we demonstrate a beam steering range of ±4° while average power consumption after the beam-shape optimization is measured to be 12.6 mW. The experimental setup, beam forming and scanning are discussed and a final analysis on future large-scale OPA integration is made.

SCIENTIFIC COLLABORATIONS: STMicroelectronics1, C2N3

Context and Challenges
With the development of LiDAR remote sensing technologies for automated driving and free-space optical (FSO) data communication technology, solid-state beam scanning has attracted great attention for future mass-market deployment. Optical phased arrays (OPA) based on silicon photonics have become an enticing solution for high-volume/low-cost scanners due to the absence of moving elements and the low unit costs associated with CMOS fabrication technology. As for their well-known radio frequency counterparts used in RADAR, OPAs consist of a multitude of individual antennas with associated phase modulators to generate and direct a diffraction-limited beam with potentially sub-mrad divergence for high spatial resolution. In order to reach typical LiDAR specifications, for automotive or mobile applications, one needs to build a circuit containing a large number of cascading components. Thus, low insertion-loss devices will have an important impact on the total optical loss. In particular, the energetic efficiency, insertion loss, power consumption and bandwidth of the integrated phase modulator have a critical influence on the performance of the OPA.

In this work, we aim to relate specifications for commercial LiDAR systems with OPA circuit specifications. We discuss phase modulator design choices before presenting a 1x16 p-i-n based OPA built on a 300-mm CMOS platform. Forming and scanning an optical beam provides some challenges in terms of electronic control and we will present how simple optimization algorithm can handle this step. Then, to plan our future integration of very large-scale OPAs, we will discuss on how to minimize optical losses of each photonic component and the reduction of random phase variations.

Main Results
We demonstrate a 1x16 silicon-based optical phased array fabricated using p-i-n phase modulators using the standard components from the STMicroelectronics photonics technology platform (PIC50G). We experimentally validated the different discrete circuit components and performed a far-field observation. We were able to create an output beam at an average power consumption of 12.6 mW and showed beam scanning from -4° to +4° with a 1° step.

Fig. 1: OPA schematics with waveguides / splitters (green), phase modulators (orange), phase value for scanning (blue) and output light (white).

 Perspectives
By considering some applications and related specifications, we analyze how to improve our future OPAs, targeting more antennas, charge depletion based phase modulators and hybrid Si/SiN architectures.

RELATED PUBLICATIONS:
Modular and versatile characterization test bench for packaged Optical Phased Arrays

RESEARCH TOPIC:
Lidar, OPA (Optical Phases Arrays), Characterization, Beam forming, Beam Steering, Temperature, Yield, Switching time


The OPA belongs to the category of active optical components. Indeed, the phase difference between the optical lengths of the OPA output channels can be dynamically modified. Therefore, the output beam is steered thanks to a set of thermal phase shifters. The principle of these phase shifters consists in heating the optical guides in order to modify their optical indexes and then their optical path. The adjustment of the phase law between the emitters confers the ability to form a beam that point towards a chosen direction to steer the beam in a given plane. The OPA do not use mechanical beam scanning. In consequence, OPA are very promising for future systems, especially for new generations of LiDARs (Light Detection and Ranging). Additional advantages of these PICs (Photonics Integrated Circuits) are their compact size with the possibility to integrate them into a “small” system. This paper focused on a modular test bench setup and various characterizations of a 1D-OPA.

Context and Challenges
This paper shows the achievement of a test bench to characterize OPA. It presents our first experimental data of a packaged and electronically driven OPA on a bench. Multiple skills and fields of expertise are required to reach this goal and all of these can be found at CEA-Grenoble:
- Mechanical, opto-mechanical and optical skills (packaging and optical set up),
- Electronics (to drive the OPA),
- FPGA programming to interface the PC and the DAC to heat the optical guides,
- Algorithms (to form the beam),
- Thermal management to maintain OPA at constant temperature,
- Instrumentation and metrology,
- Laser safety

Main Results
This OPA test bench is mainly dedicated to optical, electrical and thermal characterization tests.

The first characterizations achieved on this bench were the evaluation of the beam forming, at various angles, and at constant temperature for a 256 channels OPA

Fig. 2: Angular emission for 3 angles [-11°, 0°, +11°] after beam forming

Fully functional packaged OPAs were characterized with this test bench, specifically developed in our lab. The versatility and modularity of this bench have enabled the measurement of many figures of merit of our 256 channels OPA, which match the modeling values.

Perspectives
This test bench will be upgraded to add other functionalities such as the total power measurement at the OPA output to determine more accurately its power yield. Such test bench dedicated to evaluate the component in a real-world environment is an asset. It is a first step to go ahead to a full system by combining OPAs for emission and reception of new generations of solid state LIDAR.

RELATED PUBLICATIONS:
Scanless free space 3D FMCW Imaging

RESEARCH TOPIC:
FMCW, Lidar, 3D sensing

AUTHORS:
A. Daami, L. Frey

Three-dimensional (3D) sensing has recently been introduced in mobile devices for mass-market applications such as facial or gesture recognition. The two technologies widely used in smartphones, structured light and time of flight, are based on active imaging and enable operating in darkness. Nevertheless, ocular security constraints limit the accessible outdoor range in sunlight conditions. We present a demonstration of a free space 3D imaging FMCW bench system that is envisioned to be miniaturized for a future integration in portable applications. Our first results show a very good immunity against ambient light. We demonstrate a 3D scene imaging range of 2 meters with only 1mW optical projected-laser.

Context and Challenges
Passive 3D imaging relies on the perception of ambient light that is reflected from a given scene. Usually, the light gathered from the scene is outdoors sunlight or indoors ordinary lighting. In contrary, active 3D imaging techniques possess their own source of illumination. Generally, the lighting source is a laser. Whether, it is focused on a single point or illuminating a large surface of the scene, the use of a laser light to lighten a scene, is in itself an important advantage compared to any random illumination. Active LIDAR techniques such as structured light or time-of-flight rely on scene illumination by a light source and have the major advantage of keeping high performance in low ambient light conditions, but in return, strong ambient background such as sunlight degrades the signal to noise ratio and limits the accessible range. The FMCW LIDAR overcomes this difficulty using coherent amplification of backscattered light from the scene (SC) by a reference, or local oscillator (LO) beam. We have chosen in our work to focus on this FMCW technique to develop a scanless 3D imaging system.

Main Results
A heterodyne optical interferometer is no more than a classical interferometer with a frequency modulated light laser source (see figure 1). If \( B \) is the optical frequency modulation amplitude (usually called chirp) in a period time \( T \), one can easily determine the relationship between the scene-LO path difference \( 2z \) and the beat signal frequency \( \Delta f \) expressed as

\[
\Delta f = \frac{2 \cdot B \cdot z}{c \cdot T}
\]

The corresponding bench setup using on the shelf market components is shown on figure 2. For convenience of observation we have deliberately chosen a visible laser (633 nm). The laser output power was adjusted for eye safety to 1 mW. Figure 3 shows the 3D distance image of the imaged scene. The scanned area corresponds to 460 × 230 pixels on the camera. We observe that the distances of the different objects are well determined showing a well resolved image of the illuminated scene.

Perspectives
In order to fulfill better specifications of our 3D FMCW imaging system, we are carrying out a step towards a miniaturization of our free space bench setup with a transition to infrared wavelengths, in order to be compatible with automotive or portable applications for instance. An on-board processing of the distance information is also under evaluation. A step further towards a silicon on chip 3D FMCW scanless system is one of our ultimate goals.

RELATED PUBLICATIONS:
Luminance-depth reconstruction from compressed Time-of-Flight histograms

RESEARCH TOPIC:

AUTHORS:
Valentin Poisson, Van Thien Nguyen, William Guicquero and Gilles Sicard.

Time-Correlated Single Photon Counting (TCSPC) sensors combined with high-frequency Time-to-Digital Converters efficiently enable Time-of-Flight (ToF) imaging. This work aims at reducing hardware limitations due to the large amount of data collected in such sensors by implementing a pixel-wise ToF histogram Compressive Sensing (CS) scheme. The proposed approach demonstrates a possible reduction of hardware design constraints thanks to a typical compression ratio (CR) of more than 10x. In addition, this work presents a multimodal reconstruction based on a deep learning approach, enabling joint depth and luminance estimations, exhibiting Super-Resolution capabilities. Proper normalization layers with a learned pile-up effect compensation, multidimensional-multiscale filtering and concatenation of Softmax-ReLU activations are key design contributions to the dedicated network model.

Context and Challenges
Single Photon Avalanche Diode (SPAD) sensors used for TCSPC are particularly limited by the memory required to generate the ToF histograms (see Fig. 1). Indeed, given 10-bit coded ToF values (histograms composed of 1024 bins) and with a bin dynamic range of 10 bits, it requires 10kb of pixel-wise memory. This observation clearly motivates the use of strategies to reduce the overall amount of data collected while preserving the latent information. The goal of this work is then, first to demonstrate the interest of a novel pixel-wise histogram compression scheme at sensor level while providing a multimodal reconstruction based on a deep learning approach.

Main Results
This work [1] introduces histogram compressive sensing (CS), theoretically compatible with various TCSPC operating modes. Thanks to a custom hardware (SPAD digital readout) taking advantage of embedded pseudo-random generator (as in [2]), it allows a considerable data memory needs reduction without major loss on the reconstruction side. To support this, a "pseudo-realistic" SPAD model has been developed on which we rely to simulate Depth-Luminance map acquisitions and reconstructions. As reported in Fig. 2, depth and luminance reconstructions of natural scenes (see Fig. 3) reach more than 30dB and 25dB PSNRs for any CR higher than 2.5%.

Perspectives
Even if this work mainly focuses on the specific of Luminance and Depth rendering application, since the proposed histogram CS is somehow generic, it should be compatible with a wide range of use cases involving a TCSPC-based acquisition (e.g., gesture recognition, fluorescence lifetime imaging...).

Fig. 1: Example of a TCSPC working mode, system overview with compressed measurements (y).

Fig. 2: Average Depth (left) and Luminance (right) reconstructions PSNR versus the Compression Ratio.

Fig. 3: Example of Depth (top) - Luminance (bottom) reconstructions (right) from compressed ToF histograms (CR=2.5%) versus groundtruths (left).

RELATED PUBLICATIONS:
Composite cermet top electrodes improve pixel contrast in organic LED displays

InGaN red 625 nm micro-LEDs demonstrated on InGaNoS substrate

Surface recombination in small InGaN pixels is better understood

Photonic crystals and MQW improve color conversion in µLED displays

Direct retinal projection displays are progressing

Microelectronic fab processing produces transparent corner cube arrays for Head-Up Displays
Composite cermet top electrode for stable and high contrast organic light-emitting diodes

RESEARCH TOPIC:
OLED, Display, Cermet, Contrast ratio.

AUTHORS:
E. Quesnel, B. Caron, T. Maindran.

The OLED technology is a mature process with many display products already commercialized. Nevertheless, there is still room for improvement. In this work, we show how the introduction of nanomaterials into the upper electrode of a top-emitting OLED can enhance its contrast ratio, hence the visual comfort of the final device. This novel electrode consists of a ceramic-metal (cermet) composite thin film synthesized by co-evaporation of silver and tungsten oxide. An optimal silver content (70%) was determined that provides the electrode with, both, low resistivity (sheet resistance of 20 Ω/□) and reduced surface reflectance. As a result and with respect to conventional OLEDs, the top-emitting OLEDs integrating a cermet electrode exhibit well-enhanced contrast ratio (+77%). Moreover, this cermet technology does not affect that much the OLED device durability. A device lifetime up to 90.000 h @100 cd/m² has been extrapolated from accelerated ageing tests, value kept compatible with most OLEDs.

Context and Challenges
In the field of OLED displays, the visual comfort in bright environment is among the key requirements to fulfill. While higher display luminance can help solving this issue, alternative ways offering enhanced contrast ratio (CR) can be also considered. It generally consists in reducing the light reflectance at display surface using mostly a laminated polarizer film or more advanced solutions like a black top electrode architecture with intrinsic light absorbing properties or destructive interference filter schemes embedded in the OLED device stack.

In this work, we have investigated a novel cermet material, Ag:WO₃, used as conductive and high contrast top-electrode, in replacement of the conventional reflective semi-transparent silver electrode.

Main Results
The synthesis of the Ag:WO₃ cermet electrode by co-evaporation of both metallic and dielectric components has been optimized with respect to its sheet resistance (Rsh) and optical properties dependence with Ag content ratio. The cermet films were found to be made of Ag nanocrystals of a few nanometers size embedded in an amorphous WO₃ matrix [1]. With an Ag content of 70%, a sheet resistance of 20 Ω/□ can be obtained, in line with minimum required specifications.

With such a cermet electrode and compared to an Ag electrode, the optical simulation shows a significant reflectance decrease of the OLED top surface, on the whole visible spectral range. As a result, this new cermet electrode once inserted into the top-emitting OLED stack, offers much better contrast in a bright environment, with for instance +77% CR enhancement (compared to Ag) at 1000 lux. Such contrast improvement is visible at naked eye (insert of Fig. 2b). Moreover, standard ageing tests done on OLED using this cermet electrode predicts a device lifetime up to 90.000h at 100 cd/m², compatible with a standard use of such OLED in smartphone application for instance.

Perspectives
This technology could be advantageously used in OLED microdisplay as well as in larger OLED displays where contrast is a key requirement for a better visual comfort.

Fig. 2: a) Top-emitting OLED stack; b) OLED CR vs top-electrode type and ambient illumination. (insert: comparative picture of both kinds of OLEDs off and on).

RELATED PUBLICATIONS:
Virtual and augmented reality are emerging applications for III-nitride based micro-light emitting diodes (micro-LEDs). To obtain very bright RGB pixels on the same substrate, different approaches are possible: color conversion on top of GaN LED, or native emission with specific (In)GaN quantum well. While blue and green nitride LEDs can reach high efficiencies and very high brightness, realizing red nitride LED is still challenging due to material degradation for high Indium content quantum wells. In this work we have demonstrated the possibility to reach red emission with coherent InGaN alloy when using an adapted substrate. Internal quantum (IQE) efficiency was measured with a value above 10% at 640 nm. A 10 µm diameter circular micro-LEDs with red emission, at 625 nm, has been measured with an external quantum efficiency (EQE) of 0.14% at 8 A/cm².

Main Results
Red emitting, 10 µm diameter, circular micro-LEDs with a 4 µm diameter electrical injection area were fabricated on a Soitec InGaNOS substrate, composed of 490x490µm² partially relaxed In,Ga,N seed layer bonded on a BOX on a sapphire substrate [1]. An in-plane lattice parameter measured at 3.206Å, a good crystalline quality and an optimization of the full InGaN epitaxy LED stack have been decisive elements in enabling an IQE greater than 10% at 640nm. Indium content in the 2 nm thin quantum wells was estimated to be around 40% (B. Samuel et al J. App. Phy 129, 173105 (2021)).

A conventional chip LED process (µCC) has been applied on LED epitaxial structure. After epitaxy, V-shaped defects coming from the substrate remain, with a density of 3x10⁶/cm². V-pit density is a major issue in the performance degradation of full InGaN micro-LED, as it may create anode to cathode electrical path and enhances parasitic emission at different wavelengths. A dedicated process step to electrically isolate V-pits without degrading the quality of the p-InGaN layer has been developed, by deposition of a conformal dielectric layer before the formation of the p-contact. The final micro-LEDs exhibit an electroluminescence spectra centred at 625 nm. The EQE measured from the wafer backside is 0.14% at 8 A/cm² with an estimated extraction efficiency below 4% (Fig.1). From fluorescence and optical microscopy, micro-LEDs are emitting with a good red emission uniformity (Fig. 2).

Perspectives
Although blue, green and red LED emission have been demonstrated using the InGaNOS substrate, the realization of three colors micro-LED using a single relaxed pseudo-substrate has not been done. A monolithic approach with successive epilayers is currently under development to enable two color emissions. Additionally, an alternative approach to obtain a pseudo-substrate with a relaxation that can be adapted to each sub-pixel is investigated.
Influence of surface recombinations in III-nitride micro-LEDs: a nanoscale investigation

RESEARCH TOPIC:
MicroLEDs, GaN, display, surface recombination, cathodoluminescence

AUTHORS:
Corentin Le Maoult, David Vaufrey, Sylvain Finot1, Fabrice Donatini1, Etienne Gheeraert1, Gwénolé Jacopin1

Context and Challenges
Thanks to their high efficiency, GaN based LED are now considered as a promising candidate for micro-LED display applications. However, the LED size reduction enhances surface recombinations at the sidewall which limit the efficiency of the micro-LEDs. To mitigate such effects, there is a need of LED sidewalls passivation process and a characterization technique to evaluate its accuracy. Thus, to directly estimate the influence of size reduction on Shockley-Read-Hall recombinations and to be only sensitive to IQE variation, high spatial and high temporal resolution is required.

In this work, thanks to a spatially resolved time correlated CL setup (SRTC-CL), the carrier lifetime in a InGaN/GaN multiple quantum wells (MQW) near a mesa edge with a spatial resolution of 100nm and a time resolution better than 50 ps is measured.

Main Results
Measurements are performed on InGaN/GaN MQW stack commercially available and etched with ICP Cl3, BCl3 and Ar plasma. Figure 1A displays an example of measurements results acquired by our SRTC-CL. From Fig1B, we observed that from a distance of about 450nm from the edge, the CL signal decreases due to surface recombinations. Far from the edge, the variations of CL lifetime is correlated with CL intensity variations. In this region, both the CL lifetime and CL intensity reflect the local change in internal quantum efficiency (point defects, dislocations...). However, in a 1-μm band close to the etched surface, the situation is different. Indeed, between 450nm and 1 μm from the edge, the CL lifetime decreases while the CL intensity remains almost unaffected. Only when the distance from the e-beam to the edge is less than 450 nm, the CL intensity decreases significantly. The different trend between CL lifetime and intensity arises from a local increase in light extraction efficiency. CL lifetime profile near the edge demonstrates that surface recombination plays a role up to 1 μm which already gives an estimation of the lateral diffusion length in the MQW region.

Fig. 1: (A) CL image at MQW energy near an edge mesa, (B) Simultaneously acquired normalized intensity (black squares) and lifetime (red circles) as a function of the distance from the edge.

Next generation of high performance micro-displays should be based on III-nitride micro-LEDs. To reach high pixel densities, micro-LEDs with lateral dimension below 10 μm are mandatory. With such pixel downsampling, sidewall effects are becoming important and an understanding of the impact of non-radiative surface recombinations is required. This work deals with a methodology to quantitatively assess the influence of surface recombinations on the optical properties of InGaN/GaN quantum wells based on spatially-resolved time-correlated cathodoluminescence spectroscopy. By coupling this technique to a simple diffusion model, we demonstrate that the combination of KOH treatment and Al2O3 passivation layer drastically reduces surface recombinations.

Perspectives
Based on this approach, new simpler and shorter comparative characterization have been developed. Thanks to it, more efficient and industrial passivation process are under investigation.

RELATED PUBLICATIONS:
Enhanced conversion efficiency and tailored radiation patterns in compact MQW based color-converters for µLED applications

RESEARCH TOPIC:
High-brightness and -resolution AR microdisplays, MQW color converters, photonic-crystal, guided-wave optics, light extraction, spontaneous emission, farfield patterns and directionality.

AUTHORS:
Amade Ndiaye, Ahlem Ghazouani, Nicolas Olivier, Hai Son Nguyen, Christian Seassal, Emmanuel Drouard, and Badhise Ben Bakir

State-of-the-art quantum-dot color converters for AR glasses are failing to meet the demand for photostability and blue-light absorption. Therefore, the next generation of very bright and high-resolution AR microdisplays could rely on MQW color converters, due to their better photostability and higher blue-light absorption. However, they have not been implemented in real-life RGB microdisplays yet, because of lots of challenges related to their low light-extraction efficiency (LEE) and still Lambertian-like emission patterns, as well as their integration on on-Silicon blue µLED arrays. This work aims at investigating all the issues related to the design, fabrication and characterization of these MQW CC to pave the way for their use to achieve full-color microdisplays on a single wafer.

SCIENTIFIC COLLABORATIONS: 1 Institut des Nanotechnologies de Lyon-INL, UMR CNRS 5270, CNRS, Ecole Centrale de Lyon

Context and Challenges
As mentioned above, some challenges need to be tackled for MQW color converters (CC) to be implemented in the next generation of high-brightness and high-resolution microdisplays. The overall integration strategy investigated in this work is displayed in Fig. 1.

With proper PhC designs, we demonstrated large LEE enhancement (×8) compared to the unpatterned CC. Those high LEE enhancement factors were paired with extraction lengths far shorter than 5µm (obtained using a model based on coupled-mode theory to fit our measurements, see Fig. 2 a)) [2]. This makes the fabricated CC compatible with pixel sizes under 10µm.

Fig. 1: Schematic side view of the integration strategy

A blue-emitting µLED array is used to pump blue-to-green and blue-to-red inorganic MQW CC. In this work, we focused on blue-to-red color conversion using InGaP/AlGaInP MQW CC. The efficiency of these CC is highly limited by their low LEE. Besides, their lateral extents need to match those of the blue µLEDs (<10µm) and their light emission should be as directional as possible to avoid using additional external optics. Photonic-crystals are used as light-extractors. To better understand all the physical phenomena at play, we first study the properties of the CC itself bonded on a transparent substrate (see Fig. 1).

Main Results
Light emission in our MQW CC is governed by spontaneous emission theory, which needs to be better understood to tackle our issues. Therefore, we have first developed a novel framework for modelling spontaneous emission in layered media [1]. Using this model and rigorous electromagnetic simulations, we have designed, fabricated and tested the first AlGaInP/InGaP MQW CC fully optimized for blue-to-red and green-to-red color conversions in microdisplays.

Fig. 2: a) Measured LEE enhancement as a function of the lateral extent of the photonic crystal, b) Measured azimuthal farfield emission pattern using back-focal plane imaging

We have finally provided novel design guidelines for highly directional emission from PhC-based AlGaInP/InGaP MQW color converters (CC) in a thin-film geometry through an in-depth analysis of the measured radiation patterns. This has helped us achieve directionality up to ~5 times higher than that of Lambertian emission close to normal incidence (see Fig. 2 b)) [3]

Perspectives
The next step is to harness light emitted towards the transparent substrate using a bottom reflector on Silicon. Subsequently, we will investigate an additional way to circumvent the extraction-length issues by virtually extending the length of the device using Bloch-mode replication.

All these design guidelines will finally be used to fabricate the first-ever full color microdisplay based on MQW color converters.

RELATED PUBLICATIONS:
Manufacturing of SiN photonic circuits on transparent substrate for a retinal projector

RESEARCH TOPIC:
Integrated photonics, Glass substrate, Augmented reality

AUTHORS:
K. Millard, D. Fowler and C. Martinez

We are developing an innovative concept of Augmented Reality (AR) glasses based on the self-focusing effect of an emissive point distribution to form an image on the retina. The light is routed to the projector using Photonic Integrated Circuits embedded in the lens of a pair of glasses. As Augmented Reality devices operate in the visible spectrum, a high transparency is required on both the substrate and the circuits. This can be achieved using silicon-nitride waveguides on a glass substrate. We present the fabrication process of silicon-nitride photonic architectures. In particular, we achieve transparency by a silicon-to-glass substrate transfer. An overall 80% transparency is obtained in the device and no image alteration is found. These are promising results for future prototypes of our concept involving photonic circuits on transparent substrate.

Context and Challenges
The majority of integrated photonic devices are made of silicon (Si) waveguides in order to operate in the infrared. They are mainly used for telecommunications, OPAs and sensing. However, as Augmented Reality (AR) uses the visible spectrum, Si waveguides are no longer a valuable option because of their opacity in this wavelength range. However, silicon nitride (SiN) is an interesting replacement because of its transparency, its high refractive index and its SOI-compatibility [1]. We proposed recently a retinal projection concept that combines integrated photonics and holography. It consists of emissive points on the surface of a lens that form an image on the user's retina using the self-focusing effect [2]. Therefore, transparency of the device is required. The fabrication of our SiN singlemode waveguides is shown in Fig. 1 and described in [3]. They operate at a wavelength of 532 nm and are cladded in a SiO₂ layer. The photonic circuits are fabricated on a 200 mm silicon wafer partially oxidized.

LPCVD SiN is deposited and patterned using UV-photolithography and Reactive Ion Etching (RIE). A SiO₂ cladding layer is deposited above the circuits. The transfer to transparent substrate is performed by bonding a 500-µm thick glass handle onto the device using molecular bonding. Eventually, the silicon substrate is entirely removed using gross and fine grinding/polishing methods.

Main Results
We evaluated the overall transparency of our samples by measuring the transmission spectrum in the 400 nm - 700 nm wavelength range and the MTF (Fig. 2 (a) and (b) respectively).

Fig. 2: (a) Transmission and (b) Modulation Transfer Function of our photonic device as compared with a glass slide.

Despite a slight transmission decrease for the shortest wavelengths, we measured a device transparency between 70% and 80%. At our operating wavelength, the measured transparency is 76%. No image alteration is observed on the MTF.

Perspectives
The transparency measured on our device is a promising result as it validates its implementation in an AR projector. Future photonic devices involving a similar manufacturing will be fabricated soon and implemented in a first prototypical retinal projector for AR applications.

RELATED PUBLICATIONS:
Augmented Reality is one of the hottest topics in information technology. One of the main hardware objectives is to develop compact glasses that can efficiently display images in the eye in addition to the natural viewing. The main technologies encountered today use conventional optical design, but some recent works propose to use new principles of projection based on unconventional optics. CEA Leti has recently proposed a disruptive optical concept for AR display, it is based on the interaction of an array of monolithic linear waveguides with pixelated holograms. The image is formed on the retina with an interference effect between various beam distributions. The strategy used to address these beam distributions is part of the challenge in the development of the device. We report here our first improvement in two aspects of this strategy at the display and at the retinal plane.

**Context and Challenges**

We have proposed a Near Eye Display concept that forms an image on the retina directly from the display plane, without optical system (figure 1) [1]. The emission of light at the display plane is made through the addressing of random waveguides distributions and random electrodes distributions. The waveguide/electrode intersections form an Emissive Points Distribution (EPD). Each EPD forms a pixel on the retinal plane through an interference effect related to the coherence of the incoming light.

![Display plane](image1.png) ![Retinal plane](image2.png)

**Fig. 1:** schematic representation of the retinal display approach, a beam emitted on the display plane form a pixel on the retinal plane.

To enhance the quality of the pixels on the retina, we need to improve the number and the randomness of the Emissive Points (EPs) in each EPD. To improve the resolution of the image on the retina we need to increase the number of EPDs. The number of intersections between waveguides and electrodes and their addressing strategy in the display plane is by the way a first specific challenge in our development.

The way the pixels are formed on the retina depends also on these addressing strategies and how beams interfere. In particular, the need to avoid the effect of cross interference between pixels limits the use of the lasers in the device. This is another challenge located this time on the retinal plane.

**Main Results**

To improve the number of EPs, we define a new mathematical model to represent waveguides and electrodes using a segment succession with a unique absolute angle [2]. This patented model, represented in the figure 2(a), creates random EPDs and multiply by 3.5 the number of pixels onto the retina compared to our first model.

We solve the cross interferences issue with a patented addressing strategy of the pixel on the retina. A unique laser can be used to form various pixels if they are angularly separated on the retina by a distance fixed by the display characteristics [3]. This strategy allows us to reduce the number of lasers in the system by a factor 35. We illustrate this concept in figure 2(a) with a single laser used to address two EPDs thanks to two separated modulators. In figure 2(b) we see the two pixels formed on the retina, separated in a way they can't interfere.

![Display Plane](image3.png) ![Retinal Plane](image4.png)

**Fig. 2:** principle of addressing strategies in (a) the display and (b) the retinal plane.

**Perspectives**

The waveguide and electrode model is currently implemented on our next prototype. The cross interference avoidance will be confronted soon to experimental evaluation.

**RELATED PUBLICATIONS:**

Image angular coding evaluation for pixelated holographic Near Eye Display

RESEARCH TOPIC:
Display, holography, Augmented Reality

AUTHORS:
C. Martinez, M. Colard, M.C. Gentet, Y. Lee, P. Legentil and S. Meunier-Della-Gatta

We have introduced in 2018 an unconventional concept of Near Eye Display based on a diffractive self-focusing effect that images information directly on the retina without the use of a display and optical system. We demonstrate here a first technological brick required for the development of our device: a digital holographic recording process that encodes image angular information. This holographic set-up is used to investigate the behavior of the self-focusing effect regarding the hologram distribution. It could lead soon to first proof of concept devices.

Context and Challenges
For about ten years the development of Near Eye Displays (NED) for Augmented Reality applications has been a technological driver in optical science. But despite complex and efficient prototypes development, very few commercial devices have been commercialized and none has yet encountered public adoption. Scientists and engineers are still investigating technological ways that could lead to a real public adoption of such devices.

In 2018 CEA Leti has published a NED concept based on a complete integration of the optical system at a wafer scale [1]. Among the technological bricks required for this development, one concerns holographic digital micro-structuration. This last optical element of our device consists of sparse distributions of holographic elements (hoels) that encode image angular information. The optical activation of these distributions is expected to form an image directly on the retina with a diffractive effect called self-focusing.

We have published in 2019 an experimental validation of this effect [2]. Its validation with the use of hoels distributions was dependent of the development of an in house holographic printer. This demonstration was made at the end of 2021 [3].

Main Results
The holographic printer developed in CEA Leti is similar to a lithographic set-up. The main difference is that a coherent laser is used as an optical source and that two masks are aligned and projected on each side of the sample. After each masks recording, the sample is moved and a projection angle is modified to encode various angular information.

The use of twin masks allows recording interferences at microscopic scale in the holographic material. Typical dimension for the hoel is about 20 µm. We show in figure 1(a) a microscopic view of hoels distributions recorded with of a periodic mask (10 µm apertures, 100 µm period and printer magnification factor 2.7). The distributions of hoels encode the image angular coordinates of the letter “R”.

We show in figure 1(b) the result of the imaging process on a device that simulates the eye behavior. Due to the periodic structure of the hoels, the reconstruction of the letter is done among various diffractive orders with speckle noise. The signal averaged among the various diffractive orders allows us to visualize the self-focusing image reconstruction. As shown in figure 1(c) nearly all the image pixels, angularly encoded with a pitch 0.01°, are efficiently recovered.

Perspectives
This result is a major step in the complex development of our NED. It demonstrates our ability to encode angular information into microscopic hoels. Next step is to evaluate the same effect on sparse random distributions of hoels to get rid of the diffraction orders that limit our current field of view to 0.11°.

Fig. 1: (a) microscopic view of the hoels distributions recorded at 532 nm, (b) optical signal reflected by the hoel structure and (c) result of the image recovery (10x10 pixels) after data processing.

RELATED PUBLICATIONS:
Transparent corner cube array manufacturing process for Head-Up Display applications

RESEARCH TOPIC:
Display, HUD, Augmented Reality

AUTHORS:
C. Martinez and Y. Lee

The demand for Augmented Reality functionalities in automotive application is strong in numerous field of application, in particular for professional vehicle. It involves the implementation of Head Up Displays that are still limited in performance, in particular when the surface of the windshield is large. We have been investigating a solution based on the projection of an image directly on the surface of the windshield. It requires a complex micro-structuration of the glass, based on a corner cube replication process. We present on this contribution an efficient process for the mastering of such structuration based on microelectronic means available in CEA-Leti.

Context and Challenges
A Head Up Display (HUD) is a device that adds digital information to the field of view of the user of a vehicle. It is generally incorporated to the windshield of the vehicle. The main issues in the development of such devices are the management of both transparency and brightness of the HUD and the field of view (FOV) covered by the digital image. Conventional HUD are based on the projection of a virtual image relayed into the eye by a combiner. It allows to visualize the digital image at large distance in front of the windshield but has strong limitation in terms of FOV. To get rid of these limitation we proposed another HUD configuration based on the projection of a real image directly on the windshield. In order to see the image with good brightness, the windshield is covered by micro-structures in the form of corner cube (CC) mirrors that reflect the image back to the projector (figure 1) [1]. The user is able to see the projected image if his eyes are located close to the projector and if a diffusion behavior is incorporated into the microstructure.

Main Results
We show in figure 2 the result of our process. It consists of three main steps: 1) diffuser replication on silicon wafer, 2) Wafer to wafer bonding to bury the diffuser above a given thickness of silicon and 3) silicon deep etching to form the CC and reveal the oxide diffuser footprint layer. The process is done with a special focus on the optimization of the CC edge roughness.

Perspectives
Now that we demonstrated an efficient mastering process, next steps are to optimize the CC structure in order to demonstrate a bright HUD use case with a large FOV and validate the mastering efficiency in a plastic replication process.

Fig. 1: principle of a HUD based on the use of corner cube mirrors (on the left a detail of one CC micro-structure).

The manufacturing process of such microstructure is very challenging. CEA Leti has proposed an efficient solution to overcome this challenge thanks to a process based on Deep Reactive Ion etching of silicon buried oxide [2].

Fig. 2: microscopic and SEM images of the CC distribution, (a) top view, (b) lateral view showing de CC edges and (c) detail of the diffuser and edge roughness.

RELATED PUBLICATIONS:
RESULTATS ET FAITS INDICES

- Détection de rayons X avec MAPbBr₃
- Les paramètres d’intérêt pour la détection X sont dépendants des propriétés de transport $\rightarrow \mu, \tau, \rho, E$

Diagramme:
- Densité de photodétection
- Temp. (s)
- Sensibilité
- Trainage
- X ON
- X OFF

1 mm
• Antoine ALBOUY
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• Joël LE GALUDEC
• Titouan LEGOFF
• Corentin LE MAOULT
• Dalil OUSSALAH
• Eirini SARELLI
JORIS BARAILLON
CAVITY OPTOMECHANICS BASED ON THE "MEMBRANE-IN-THE-MIDDLE" SETUP: THEORETICAL AND APPLIED STUDIES IN THE NEAR AND MID-INFRARED REGION
Université Grenoble Alpes (France)

This thesis deals with the development of optomechanical spectroscopic cavities in the mid-infrared wavelength range (MIR, between 3 and 12 μm). Indeed, in this spectral range, detectors have a degraded detectivity compared to visible or even near infrared detectors.

This work finally extends the field of cavity optomechanics to the MIR range, opening the latter to various sensor applications.

The "membrane-in-the-middle" (MIM) system, composed of a membrane suspended in a Fabry Perot cavity, has been chosen. We have designed an optomechanical microcavity based on this architecture and a microfabrication process in silicon technology. They have been designed specifically for the detection of carbon dioxide (CO2), via the measurement of the mechanical resonance frequency shift induced by the absorption losses minimizing the impact of the optical spring effect. The limit of detection in the case of traces of CO2 is numerically estimated between 10 and 100 ppb (parts per billion), based on analytical analyses coupled with multiphysics finite element simulations.

We have implemented a new type of hybrid MIM cavity using lensed fiber Bragg gratings and dielectric mirrors in the near infrared region (NIR, 1.55 μm). We have characterized on a dedicated bench the thermomechanical motion of...
Using semiconductor materials instead of the scintillators currently used in medical radiography would allow increasing both the X-ray sensitivity and the spatial resolution of imagers. However, to date, no semiconductor material is compatible with the specifications of large area (40 cm × 40 cm) medical radiography. The objective of this work is to assess the viability of halide perovskites for medical radiography. Cr/MAPbBr\textsubscript{3}/Cr type devices are used as a study model to meet this objective. The first part of the study focuses on the measurement of the interest parameters for X-ray detection. Three observations can be drawn from this study. Firstly, the sensitivity under X-ray irradiation measured is twice that of the scintillators usually used but does not reach its theoretical maximum value. Secondly, the dark current is at least two orders of magnitude too high. Thirdly, the noise limits the counting performances of the devices. The second part of the study focuses on understanding the physical origin of the limits observed on the detection parameters. Four conclusions can be made from this study. First, the growth conditions and crystals’ quality cannot be correlated to the detection performances. Second, the sensitivity depends on both the electrons’ and holes’ transport properties and the electric field distribution within the devices. Third, the dynamics of the dark current are linked to the ionic migrations in the devices. Fourth, the noise measured for the frequencies of interest of gamma spectroscopy (10 kHz-20 MHz) reveal that the 1/f noise dominates at frequencies < 200 kHz.

The passive stand-off submillimeter-wave (SMMW) imaging is suitable to detect hidden objects (weapons, explosives) through clothes or bags and also to image through Degraded Visual Environment (DVE) like brown-out clouds. However, the required detectable power under one picowatt is very challenging to obtain. Current available systems are hampered by their very low temperature cryogenics, near liquid helium, which increase their size. This PhD project aims to assess the performance of a detector based on antenna-coupled microbolometer, with intermediate cooling, compatible with CMOS process flow and thus convenient for focal plane array integration. The thermometer element of the bolometer is based on a cooled silicon lateral diode, whose thermal properties have been studied theoretically and experimentally. A temperature coefficient of current exceeding 20 %/K at 80 K in low injection forward bias is reported, i.e. ten times higher than regular uncooled thermistor materials. The diffusion regime is found to be the most relevant to minimize the thermal resolution of such silicon p-n junction thermometer. In a second time, a sub-THz pixel has been designed thanks to 3D finite element simulations. An optimized coupling between a patch antenna and a resistive dipole, with a 250-μm pixel pitch, led to near 90 %.
MAXIME BRONCHY
DEVELOPMENT OF A SILVER NANOCUBES-BASED FORMULATION FOR SEMI-CONDUCTOR INTEGRATION BY LOW TEMPERATURE SINTERING
Université Grenoble Alpes (France)

Metallic interconnection materials are of high interest in numerous power electronic packaging applications. Among new methods of integrating semiconductor dies on a dielectric substrate, sintering stands out as an promising alternative. It makes it possible to produce a dense and robust metallic junction at low temperature, compatible with an higher operating temperature. Sintering based on micro- and/or nano-silver particles is the best known in view of its excellent mechanical, thermal and electric properties. The particles can be densified using a heat treatment, at a temperature which is much lower than the melting temperature of bulk silver, in a few hours, with or without pressure. This approach is marketed in the form of sinter paste, the deposition of which can be carried out by screen printing and the sintering cycle carried out in air. In this study, we explore how the design parameters of nanoparticles can be modified to improve the efficiency of sintered Ag technology. We investigated the potential of a paste based on silver nanocubes well-calibrated in size and shape to achieve thick silver joints, sintered at low temperature and pressureless. Silver nanocubes of different sizes were produced by wet colloidal approaches in polyol and aqueous mediums. Their thermal stability was investigated at the single particle level and for assemblies of multiple particles. Their integration into a printable paste allowed a reduction in the sintering temperature at ambient pressure during sintering cycles.

ALEXI CARDOSO
THERMAL IMMUNITY OF THE SENSITIVE MATERIALS IN MICROBOLOMETERS
Université Grenoble Alpes (France)

The development of consumer uncooled microbolometers has much progressed in recent years, due to increased market demand in security/surveillance, smart building, automotive and outdoors leisure. To improve bolometric performance in terms of TCR and 1/f noise, CEA/LETI has developed, in collaboration with the industrial LYNRED, bolometers based on transition metal oxides. However, despite better overall performance compared to the amorphous silicon counterparts, these new materials are prone to damage during routine high temperature device fabrication steps and are more affected by sunburn persistence. In this thesis, we have sought to identify the physicochemical mechanisms that explain why the thermal stability of the thermometer materials is improved when we change their chemical composition. Both laboratory and synchrotron radiation characterization techniques (FTIR, Raman scattering while heating or at ambient temperature, thermal 4-points probe resistivity measurements, XRD, TEM, EXAFS) have been done, but also ab initio computer simulations of the state of the art to study the microscopic structure of the studied materials. Moreover, to address the sunburn problem, we have developed the innovative experimental characterization “high speed quench” (TGV in French), to study the relaxation mechanisms that occur after applying a specific thermal treatment (characteristic of sunburn phenomenon) to the thermometric materials.
A plenoptic sensor enables the capture of a light field: it spatially and angularly samples the light rays coming from a scene, unlike a conventional image sensor which only allows spatial sampling. This offers more possibilities in terms of image processing. For example, one can refocus the image after its acquisition. It is also possible to correct lens' aberrations, or calculate a depth map in a passive way. The angular sampling is achieved by placing multiple sub-pixels under a single microlens of the sensor. This thesis focuses on the case where a microlens covers a patch of 2x2 sub-pixels, called a quad-pixel. Its object is to link two of the three aspects of the imaging system, the pixels on the one hand, and the image processing on the other hand. The lens used to produce the image on the sensor is not studied here. First, I present simulations at pixel level, mainly using 1.75 microns subpixels. Given the defined metric performance, I present some solutions in order to improve the performance of the pixels. Based on these simulations, I decided to modify a ray tracing renderer in order to take into account the diffraction in microlenses. It then made it possible to generate synthetic images and thus study the image processing algorithms. I show that microlens diffraction tends to degrade the algorithms' performance by studying the case of aberration correction of the main lens. I also present multiple ways to use a quad-pixel, using deep learning techniques and neural networks, such as debayering or diffraction removal.
After first developments at CEA-Leti on curved sensors and the demonstration of highly compact optical systems benefiting from curvature, this thesis explores the use of curved microdisplays in visuals systems to make them more compact. Advantages of curved microdisplays in visual freeform optical systems are studied theoretically. The curvature allows a better correction of field curvature aberration and of distortion. Also, the curvature allows improving the flux transmitted from the microdisplay to the optical system. Under most favorable circumstances, the gains reach about 20%. For freeform systems, the curvature frees some new degrees of freeform, which can then be used to improve the compactness of the final system, its image quality or simplify its manufacturing. The possibility of combining all these positive impacts is a major result of this work. After these theoretical studies, two optical systems are designed, and one of them is manufactured and characterized. The first is an augmented reality viewfinder, made of three freeform prisms bond together. It is meant to be used in cameras and demonstrates the benefits of using curved microdisplays on image quality, compactness and luminous flux. The second system is the one which is manufactured. It is a conventional electronic viewfinder demonstrating the benefits of curvature regarding compactness and easier manufacturing of the device. Its characterization includes a measure of the contrast and a visual test.
Thanks to its low cost and practical advantages, Petri dish culture is a ubiquitous tool in microbiology, but the sole observation of microbial colonies does not offer a reliable diagnosis. Identification in itself depends on secondary analysis, such as chemical reactions, PCR or mass spectrometry, which require specific sample preparation, which involves additional costs and delays. That is why several dish imaging systems have already been tested to automate the observation of cultures and to propose an identification directly on the Petri dish. However, these systems are generally limited to the visible and near infrared range (400 - 1000 nm), which only provides information on the morphotype of the microorganism colonies and therefore limits the identification accuracy. This thesis focuses on the development of a multispectral imaging system in the mid-infrared. In this wavelength range, images provide information on both the morphotype and the chemical composition of the observed colonies. This non-destructive and label-free imaging could provide species identification of colonies grown on agar, while opening the way to new applications. An experimental system, combining quantum cascade lasers as a light source and a microbolometers array as an imager, allowed the acquisition of images of colonies at nine wavelengths between 5 and 8 µm. After acquisition, several image classification methods of eight species of common microorganisms were tested to obtain an average correct identification rate of 94.4%.

For astronomy applications, the expected performance level of Infra-Red (IR) detectors is extremely high. However, one remaining characteristic limits the scientific use of these detectors: the persistence. In short terms, previous images leave their imprint and pollute the following images with time constants of the order of hours. However, current developments marginally take into account this phenomenon, which is yet present on today's detectors from US industries. Neither physical mechanisms involved nor technological steps responsible for this degradation are known. Consequently, this thesis proposes an experimental study of persistence based on detectors directly manufactured in CEA-LETI clean rooms. Theses detectors are HgCdTe large format (2048x2048 15µm pitch pixels) sensitive to the 0.8-2.1µm spectral band. For this industrialization, an improvement on the persistence criteria would be a crucial advantage compared to existing detectors. Passivation, degradations related to the diode formation process and bulk defects in the absorbing layer are especially revealed as major contributors. The impact of these technological steps had never been observed with classical characterization techniques, hence the importance of developed protocols in the frame of the detector industry. Finally, these measurements are compared with an analytical model of persistence. It allows estimating that a trap density on the order of residual doping is sufficient to explain observed persistence on some detectors.
The gallium nitride (GaN) µLED is a prime candidate to meet the specifications of new augmented reality applications and could also find its place in a wider range of applications in the longer term. However, the high perimeter-to-surface ratio of µLEDs makes them very sensitive to edge defects generated by pixelation etching. Therefore, passivation post-treatment steps of the µLEDs sidewalls must be implemented and optimized in order to minimize the decrease in efficiency that inorganic µLEDs are facing more generally. This constitutes the problematic of this thesis, dealing more specifically with GaN/InGaN blue µLEDs. First, this thesis has attempted to identify the most promising path for the passivation of GaN µLEDs from the literature. Then, physicochemical characterizations allowed to study the effect of chemical treatments or alumina deposition by ALD (Atomic Layer Deposition) methods on the surface properties of InGaN from µLEDs active region. Some specific behaviors have been observed especially after treatments with hydrochloric acid or ammonium sulfide, rather effective in reducing the amount of indium on the surface, or even oxidation of the latter. However, an ammonia treatment would be more favorable to enhance ALD passivation layer nucleation, which is just as important for the quality of the interface.

For user convenience, the 3D imaging and facial recognition in the smartphones operates in the IR. Therefore, in the last few years, the NIR/SWIR imaging market has grown significantly. This thesis developed an IR-sensitive organic photodiode (OPD) that is low cost and compatible with integration on CMOS readout circuits. To optimize the device structure and the fab, we started with a visible-range OPD. A doped organic transport layers (Hole/Electron transport layer (H/ETL)) was optimized by studying the effect of the thickness of the doped HTL layer on its output work function. Our simulations were experimentally validated on a F4TCNQ doped HTL layer of STTB. The second part of the thesis dealt with an infrared OPD while following two approaches: 1) using complex charge-transfer molecules with strong SWIR absorption 2) functionalizing small molecules from the skeleton of a known basic molecule, to reduce the optical gap and obtain a sensitivity in the IR.
To realize new generations of RGB (red-green-blue) microdisplay, the GaN based micro-LEDs can fulfill the needs for a high-quality depiction with a pixel pitch of less than 10 μm x 10 μm. InGaN/GaN quantum wells (QW) combined with quantum dots (QDs) is one of the major strategies towards the realization of green and red pixels. However, the advantages, the interaction between the blue LEDs and the QDs is limited by optical losses. Here, we study the non-radiative energy transfer (NRET) as an alternative coupling mechanism to overcome the issue of losses and to improve the color conversion efficiency in compact, low consumption RGB micro-LED.

The NRET is an emissionless dipole-dipole interaction and the main parameters that can affect it according to the theory are the: donor dipole orientation, the donor-acceptor distance and the local density of optical states (LDOS). We first investigate the dipole orientation in a InGaN QW. By varying the GaN cap layer thickness on top of the QW, we aim at controlling the dipole electromagnetic environment and observe the impact on its orientation. The observations are coupled with the detection of polarized emission from the structure. By addressing the limits of the donor-acceptor distance, we evaluate theoretically the energy transfer between InGaN and QDs. Lastly, we address the impact of LDOS. With the implementation of photonic crystal structures that support resonances in the red or in the green, we aim at creating suitable conditions that may give rise to the energy transfer between green and red QDs.
GREETINGS

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