VISIR – Novel combined Visible Infrared photodetectors

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ABSTRACT
Extending and controlling the spectral range of CMOS image sensors is a lively research area driven by the envisioned applications in automotive, healthcare and machine vision. In this framework, the VISIR project aims to realize photodetectors with a bias controllable spectral response covering both the visible and short-wave infrared spectral regions and to design a suitable CMOS read-out integrated circuit.

Keywords: Image Sensors; Visible light; Short-Wave Infrared (SWIR); CMOS: Readout Integrated Circuit; ROIC

1. INTRODUCTION

Extending the spectral coverage of CMOS image sensors toward the short-wave infrared (SWIR) is extremely relevant for many technological applications, in particular:

- The SWIR light reflected by an object carries valuable information about its composition, with countless applications in healthcare, food quality control, machine vision and waste recycling.
- Thanks to the longer wavelength, with respect to visible (VIS) light, the SWIR suffers less scattering by fog, dust and smoke, making this spectral region ideal to increase drive safety in bad weather conditions.
- The light naturally emitted by the atmosphere during the night is particularly intense in the SWIR, allowing the development of a new class of night-vision sensors.

SWIR represents an outstanding opportunity due to the increasing demand for applications in automotive, industrial automation and healthcare, but the high costs of commercially available SWIR imaging systems, which typically exceed 5 k€, are strongly hindering the growth of the market, which is expected to reach 100 M€ in 2025. There is also an increasing demand for multispectral imaging systems operating in the VIS-SWIR spectral region and capable of distinguish the two spectral channels. At the moment such functionality can be obtained only by combining the images recorded by two different sensors.

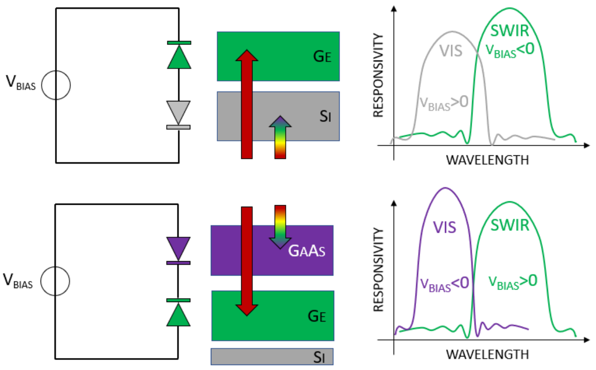

Fig. 1. Principle of operation of the back-to-back phodiodiodes.

In this context we are developing cost-effective, high performance, multispectral VIS-SWIR photodetectors based on two different material stacks. The first one is based on a Ge thin film deposited on a Si substrate. The second one is based on a GaAs thin film deposited on a Ge-on-Si substrate. For both the material stacks, the Ge layer constitutes the SWIR sensitive material, while the VIS is absorbed by the Si substrate and by the GaAs thin film respectively. The two photosensitive layers are structured as “back-to-back” photodiodes, allowing the separate selection of each spectral band simply by switching the polarity of the externally applied bias voltage. (see Fig. 1). Thanks to the monolithic integration on Si, both the material stacks are suitable for mass production of cost-effective VIS-SWIR image sensors. In addition, the optical responsivity of such structures is highly dependent on the applied bias voltage. This feature can be exploited to spectrally resolve the light reflected by an object without any need for dispersive optical elements or filters, paving the way toward the realization of hyperspectral image sensors.

During the phase I of the VISIR project we have designed, fabricated and characterized single pixel photodetectors as a first step toward the realization of VIS-SWIR multispectral image sensors. The results have been used in the definition of an architecture for the CMOS ROIC.

2. STATE OF THE ART

The technology of image sensors operating in the VIS spectral region is dominated by silicon, which offers the best performances in terms of peak specific detectivity (D*) (≈10^{12} cm $Hz^{1/2}$ W^{-1}) and resolution (up to 7920x6004). Taking advantage of the large production volumes and of the direct integration of the detectors with the CMOS ROIC, nowadays Si based image sensors have prices in the 10-100 euro/device. As a consequence, Si-based image sensors are ubiquitous, and the market volume is expected to reach 45 B€ in 2025. The SWIR spectral region has attracted some interest only in the last ten years. The most advanced technology for image sensors operating at these wavelengths is based on InGaAs photodiode arrays on InP substrates integrated with CMOS ROICs [1]. Systems operating in the 0.9-1.7 µm and 1.0-2.35 µm ranges have recently become available, both based on linear and two-dimensional arrays with resolutions from 320x256, 640x480, up to a maximum of 1280x1024 and peak specific detectivities up to 10^{13} cm $Hz^{1/2}$ W^{-1} [2]. As mentioned before, SWIR imaging systems based on InGaAs/InP have high costs (10-50 keuros) and are not suitable for high volume applications. A SWIR image sensor based on colloidal PbS quantum dots hybridly integrated with a CMOS ROIC has been recently marketed by SWIR Vision System [3]. This imaging system operates between 0.4-1.7 µm with a peak specific detectivity of $D^* = 1x10^{12}$ cm $Hz^{1/2}$ W^{-1}. Two dimensional arrays with cuts of 640x512, 1280x1024 and 1920x1080 are available, with prices starting from ≈ 20 keuros.

Tab. 1. Comparison of VISIR photodiodes with the current state-of-the-art.

Technology	Cost (€/device)	Spectral coverage (µm)	Peak D* cm $Hz^{1/2}$ W^{-1}
InGaAs	>10000	0.9-2.35	10^{12}
PbS QD	>20000	0.4-1.7	10^{13}
Si	10-100	0.4-1.1	10^{13}
VISIR prototypes	100-1000 (estimated)	0.4-1.6	$7x10^{11}$

At the moment, multispectral imaging in the VIS-SWIR spectral region can be implemented only by using two different image sensors (Si-based for the VIS and InGaAs-based for the SWIR) and operating an image fusion by software [4].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The evolution of the imaging market for CMOS visible light image sensors [5] and infra-red imagers [6] shows a double-digit growth in many fields. In 2021, the absolute value of the market will be 15 and 3.2 billion USD for VIS and SWIR imagers respectively. In the SWIR field, the range of applications is wide including, as well surveillance, firefighting, maritime or unmanned aerial vehicles (UAV), and the market is very dynamic so that new applications could arise. The VISIR technology is well placed for the existing applications and will confidently win market shares in new applications.

As a matter of fact, today SWIR imaging is poorly exploited compared to the opportunities that it offers. As already mentioned, the high cost of the commercially available imaging systems is the main factor limiting the growth of the market. In this framework, the technology developed within the VISIR project will allow the production of cost-effective image sensors with a price range comprised between 100-1000 €/device. Both the material stacks under investigation can be deposited monolithically on large Si substrates, allowing large production volumes and easy integration with CMOS ROICs. The capability of simultaneous detection of VIS and SWIR spectral channels on the same pixel allows to easily implement image fusion at the device level, eliminating the need of complex algorithms for image mixing and object recognition. The strong bias dependence of the optical responsivity of the detectors can be exploited to spectrally resolve the light reflected by an object without any need for dispersive optical

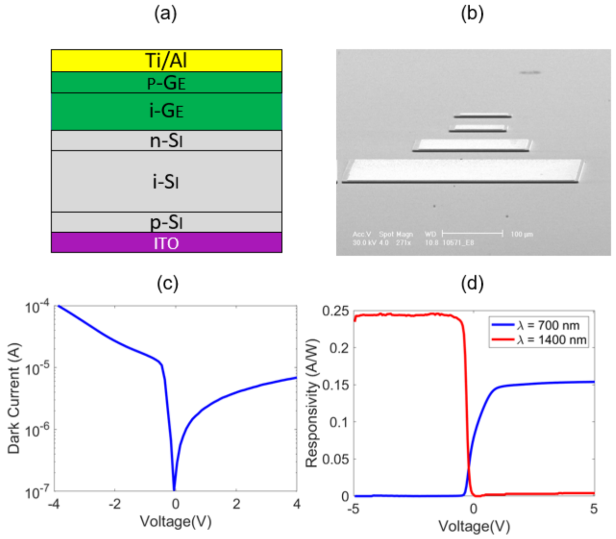

Fig. 2. Schematic of the device with epitaxial layers (a), SEM image of the processed devices (b), Dark current (c) and responsivity (d).

elements or filters, paving the way toward the realization of a new class of simple and compact hyperspectral image sensors.

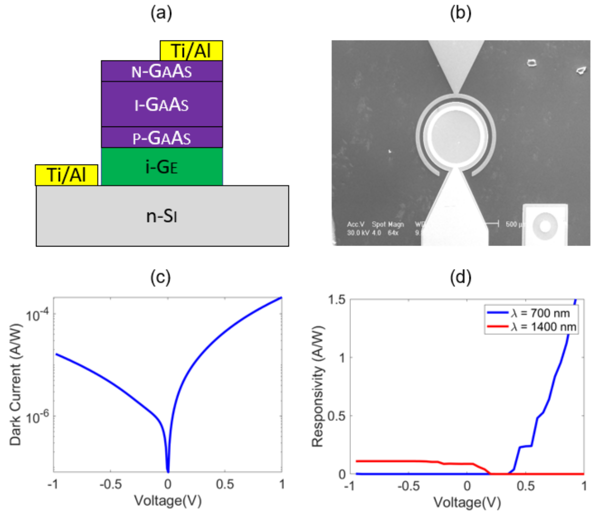

Fig. 3. Schematic of the device with epitaxial layers (a), SEM image of the processed devices (b), Dark current (c) and responsivity (d).

4. PROJECT RESULTS

Ge/Si detector.

The sample has been grown by LEPECVD [7] on a nominally intrinsic 100 mm silicon (001) wafer. Before the growth, the rear side of the substrate has been treated with a spin-on-dopant to form a p-type layer that will serve as bottom contact for the devices.

The first part of the structure consists in a 200 nm thick n-type (5x10^{18} cm^{-3}) Si layer grown at 760°C. Then a 3 µm thick nominally undoped Ge thin film has been deposited at 500°C, followed by six cycles of thermal annealing between 600-780°C to improve the crystalline quality. Last, a p-type (5x10^{18} cm^{-3}) Ge layer has been deposited to form the top contact of the structures. Isolated square photodiodes with diameters spacing between 100-500 µm have then been processed by standard UV lithography and dry etching. The top contact has been realized by a Ti/Al (100 nm/1µm) metal stack realized by e-beam evaporation, while the bottom contact has been made by sputtering of 200 nm of ITO. A schematic of the device is reported in Fig. X(a). The IV curves and the responsivity of the devices as a function of the applied bias are reported in Fig 2(c) and (d) respectively. The peak specific detectivities of the device are $7\cdot10^{11}$ cm√Hz/W in the visible and $2\cdot10^{10}$ cm√Hz/W in the SWIR.

GaAs/Ge/Si detector

The sample has been grown by LEPECVD and MBE on a n-doped 76 mm silicon (001-6° miscut toward <110>) wafer. The first part of the structure consists in a nominally undoped 1 µm thick Ge layer grown at 500°C by LEPECVD followed by six cycles of thermal annealing between 600-780°C to improve the crystalline quality. The Ge thin film serves as the SWIR sensitive layer and as a virtual substrate for the subsequent GaAs deposition. The wafers were then transferred in an MBE. After performing an annealing step at 650°C, the Ge surface is exposed to an As flux followed by the deposition of 100 nm of $Al_{0.8}GaAs$ doped with Be. Then the diode structure is grown by depositing 100 nm of p-doped GaAs, 1700 nm of undoped GaAs and finally 200 nm of n doped

The concentration for both Be (p dopant) and Si (n dopant) is.2×10^{18} cm^{-3}. Isolated circular photodiodes with diameters spacing between 100-500 µm have then been processed by UV lithography, wet etching (for the GaAs) and dry etching (for the Ge layer). The top contact has been realized by the deposition of an AuGeNi metal stack on the n-GaAs layer followed by an annealing at 420 °C for 5 minutes. The bottom contact is made by an Ti/Au metal stack directly deposited on the n-type Si substrate. The maximum responsivities are 1.5 A/W and 0.1 A/W in the VIS and SWIR respectively. The detectivity measurement is ongoing.

These preliminary results show that both the material stacks can detect light in the VIS-SWIR spectral region and that the two spectral channels can be separately acquired just by switching the sign of the voltage bias applied to the device.

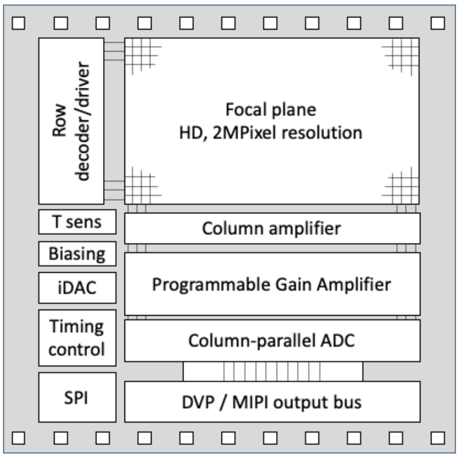

Fig. 4. Floorplan of the VISIR Phase 2 image sensor.

CMOS Readout Integrated Circuit (ROIC)

We developed an architecture suitable for a Phase 2 imager. Pixel simulation shows performance at the same level of competition could be achieved. The figure below shows the architecture of the sensor that, together with the focal plane array with HD resolution, would integrate all the readout circuitry:

- column amplifier and column-parallel programmable gain amplifiers (PGA). The gain can be adjusted to cope with different scene illumination levels.
- column parallel analogue-to-digital converters (ADC). We have an architecture where the bit depth of the ADC can be traded against the speed of conversion, and would work for high speed applications as well
- output bus with a standard imaging format, e.g. digital video port (DVP) or MIPI, which uses a low voltage differential signals (LVDS) physical layer.

The sensor will also be programmable through a proprietary serial-to-parallel interface (SPI). The timing circuitry will generate all the needed internal signal and the current digital-to-analogue converter (iDAC) will generate all bias currents and, coupled with a current-to-voltage converter, bias voltages. At least one temperature sensor will be integrated to provide monitoring of the on-chip temperature.

5. FUTURE PROJECT VISION

As explained above, the potential of the VISIR technology cannot be overstated and its impact can be manifold. Having obtained good results on single-diode detectors, we now want to move to the integration of this technology with an imager ROIC, so that combined high resolution imaging in VIS and SWIR can be obtained.

Tab. 2. Possible composition of the ATTRACT Phase 2 VISIR consortium.

Role	Partner
Material growth	Uni Mi
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Material simulation and characterisation	Uni Roma
CIS and camera design	IMASENIC
GaAs growth	*Partner X*
Ge growth	*Partner Y*
End-user / lead customer	*Partner W*

5.1. Technology Scaling

During the 1st year of the VISIR project, we demonstrated the properties of the basic material with single element detectors with external electronics. In order to fulfil our vision, we plan to move the material growth to more advanced facilities, using the recipes we have developed during this 1st year. We have already identified and interact with renowned European facilities, specialised in the growth of either GaAs or Ge. These facilities will allow us to rapidly move to the production of pixelated substrates on 6 and 8” wafers, as well as to hybridise them with the CMOS ROIC.

With the larger funding available in the Phase 2 ATTRACT call, we will also be able to manufacture the ROIC optimised according to the architecture developed in Phase 1. For the manufacturing of the ROIC; we will use state-of-art CMOS foundries, that we routinely used for our products.

5.2. Project Synergies and Outreach

As explained in the previous section, we are planning to expand the consortium with other partners. The discussion has already started with partners for the growth of Ge as well as GaAs. We have also started liaising with some industrial end-users. A possible composition of the consortium is shown in Tab. 2 here.

5.3. Technology application and demonstration cases

Over the next decade and beyond, the ubiquity of the VISIR technology will help our society face many of the current challenges as well as new ones.

The applications for VISIR are very diverse, addressing both scientific and industrial area, with a significant impact on societal challenges. In science, we anticipate VISIR detectors will have a major impact in all applications where its main characteristics, compact, uncooled, low weight, robust fast and spectrally resolved, could provide a substantial advantage. One of these areas is Earth observation studies, where coupled to dispersive optics, the VISIR detector will permit hyperspectral resolution imaging in a wide spectral range with a compact, low weight, low cost but high-performance system. It will enable astronomical instruments, as well as monitor of emissions and chemical contamination, crop development and health, sea observation and to detect the chemical composition of plants when mounted on small satellite platforms (integrated into constellations) or unmanned aerial vehicles (UAV). These observations will greatly enhance our understanding of climate effects. In medicine, as the VISIR spectral range matches well the so-called NIR therapeutic window (650-1350 nm), where the depth of penetration in tissue is maxima, it would benefit non-invasive studies, e.g. for disease prevention. Fast IR signals generated by firing neurons could be studied with a high-resolution imaging, and through the understanding of these phenomena, efficient brain-computer interfaces [8] could be developed. In food industry, VISIR detectors can be used for real-time monitor of products contamination. Thanks to its speed and broadband capability, our sensor will also find applications at high-brilliance light sources, like synchrotrons or free-electron lasers. It should also be said that the development of processes for the integration of semiconductor heterostructures on silicon CMOS circuits will constitute a major scientific breakthrough per-se. A high-quality GaAs/Ge/Si material is a fundamental platform to implement a family of complex detectors, extending from VIS to LWIR, with extreme wide potential applications.

In industry, the applications of uncooled SWIR imagers are very wide [6]. With its combined VIS-SWIR sensitivity and the speed of the material used, the VISIR sensor could provide a high resolution 2D imaging with the possibility of providing accurate time-of-flight TOF measurement for depth information. The VISIR sensor could enable accurate 3D imagers, which are becoming increasingly requested for applications like robotics, gaming, virtual/augmented/mixed (AR/VR/MR) reality or car industry. In this latter, there is today a tremendous push towards fully autonomous vehicles, using Advanced Driver Assistance Systems (ADAS). The industry goal is to have fully autonomous driving by the middle of the next decade, and, as for other technology uptakes in the same industry. The VISIR technology matches well to the needs of ADAS, as it provides not only imaging but also depth information in VIS and SWIR. A SWIR camera is also capable to see through smoke and fog as well as detect water and ice and see at night, even in moonless nights. VISIR could then be used in fully autonomous vehicles, and on the way to this ambitious goal, it will enhance or enable visual aid systems. The existence of better ADAS could have an impact of a few percentage of the Gross Domestic Product (GDP) which is the estimated cost of road crashes in developed countries.

5.4. Technology commercialization

Already in Phase 1, the VISIR consortium has a mixture of academic and commercial partners. In phase 2, we are planning to add partners that would be able to grow the device on a larger surface and integrate it with the ROIC. The size of the surface would allow wafer-scale integration of the material together with the ROIC, which is likely to be made in a CMOS technology on 200 mm diameter wafers. As both Ge and GaAs need to be grown, it is possible that two different partners, each specific to one of the two materials, will be included in the consortium. The CIS as well as the surrounding electronics will be integrated in a camera developed by IMASENIC. We aim to introduce a lead customer to the project. This would provide an efficient route to the commercialisation of the VISIR camera. We are confident that, with this mixture of partners, VISIR will be able to achieve TRL 7 at the end of Phase 2.

5.5. Envisioned risks

While Phase 1 demonstrated the performance of the device and its ability to be electrically tuned to different spectral bands, one of the main points of Phase 2 will be to be able to produce the material on a large area and in a reliable way. The choice of the partners for the Phase 2 will be essential in order to minimise risks and reduce the time-to-market of the Phase 2 VISIR high resolution imager.

5.6. Liaison with Student Teams and Socio-Economic Study

The presence of three renowned university teams in the Phase 1 project as well as in its Phase 2 continuation guarantees that the link with student teams and socio-economic studies will be strong. The founder of IMASENIC, the other member of the Phase 1 Attract and likely to be also the leading team in the Phase 2 proposal, also had the first part of his career spent in academia or research organisation and is still giving invited talks at a number of international conferences. Other potential consortium members could also be leveraged from the research area, especially the partner specialised in material growth on large surface. This combination makes the VISIR Phase 2 consortium an excellent ecosystem for MsC level projects.

With his excellent background in dissemination of the results, as proven by a wealthy number of publications in internationally renowned journals, the VISIR team will continue this activity through the Phase 2 proposal. We envisage to publish at least one white paper about the technology that we are developing.

6. ACKNOWLEDGEMENT

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