A 10-bit 10x10 25µm-Pixel NIR Camera Using Backside-illuminated Ge-on-Si Detectors and Ultra-low-power Direct-injection ROICs

Steffen Epple[1], Zili Yu[1], Mathias Kaschel[1], Michael Oehme[2], Maurice Warnitzek[2], Joerg Schulze[2], Joachim N. Burghartz[1]

[1] Institut für Mikroelektronik Stuttgart (IMS CHIPS), Allmandring 30a, 70569 Stuttgart, Germany, epple@ims-chips.de, +49 711 21855-329

[2] Institut für Halbleitertechnik (IHT), Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany

Introduction

Near-Infrared (NIR) detectors experience an increased demand in various applications [1], e.g. environmental, critical vision, spectroscopy, etc. For detector applications up to λ = 1.1 µm it's possible to use the cost-effective Si technology, but for near infrared region Si is transparent and cannot be used to detect optical radiation. Therefore state-of-the-art NIR detectors are made from III-V semiconductors such as InGaAs. However, they're not CMOS (Complementary Metal Oxide Semiconductor) compatible, which results in high production costs. An attractive alternative is to use CMOS-compatible Ge-on-Si detectors, as they have a very similar spectral sensitivity in the NIR range [2, 3], in which Ge is epitaxially grown on a Si substrate. Fig. 1 verifies that germanium delivers as good absorption-coefficient as InGaAs. Thereby the Ge acts as an optical absorber for radiation up to λ ≤ 1.8 µm, while the Si is used as a low-cost carrier substrate as well as for the integration of further electronic functions [6].

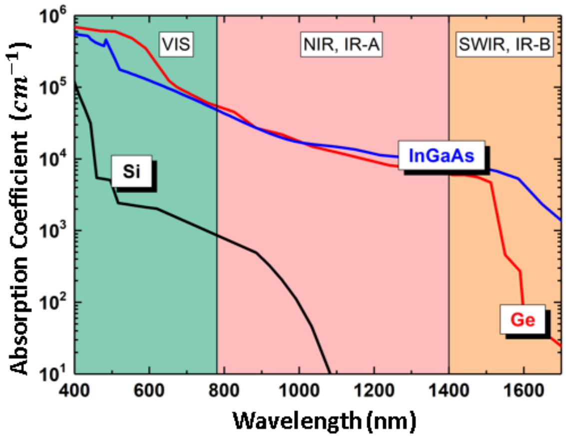

Figure 1 Absorption coefficient of Ge compared to InGaAs and Si as a function of wavelength

Such a 10x10 Ge-on-Si detector array has been designed by IMS CHIPS and IHT University Stuttgart for a night-vision camera application. It consists of a photonic chip with the Ge-on-Si detectors, the readout integrated circuit (ROIC), a microcontroller to operate the camera and a graphical user interface (GUI) to visualize data. In the following the single components and design considerations are described, starting from the Ge-on-Si detectors to the front-end and back-end electronics.

Ge-on-Si Detectors

The Ge-on-Si pin photodetectors are processed by slightly adjusted MEMS (Micro-Electro-Mechanical Systems), CMOS and packaging processes with an additional epitaxy layer (Fig. 2). The Ge-on-Si detectors consist of a stacked layout with a Si substrate as base material, an epitaxial grown Ge layer as intermediate absorber and on top the metal interconnections.

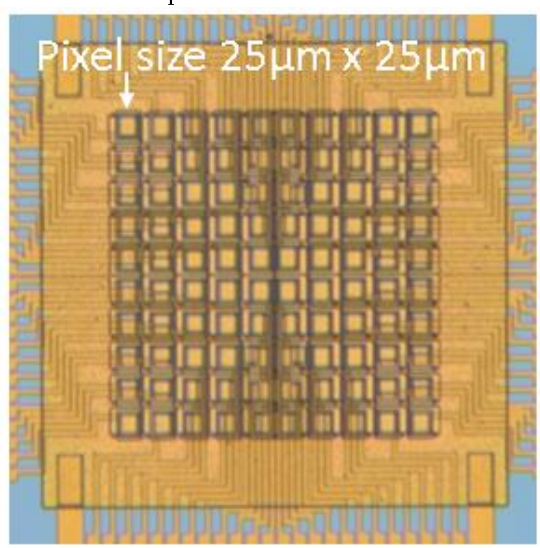

Figure 2 Die photo of the fabricated 10x10 Ge-on-Si pixel detector array

The Ge-on-Si detectors are used in a backside illuminated manner, because this brings several great benefits, which builds a solid base for the 10-bit 10x10 Ge-on-Si NIR camera:

Firstly the detector surface is not shaded by the metal interconnections, a high fill factor of 74% with a small pitch distance of only 25µm can be achieved. Secondly by the backside illumination the intense daylight exposure to the photonic chip is filtered out, because the Si substrate completely absorbs light for wavelengths smaller than 1µm. Thirdly through the backside illumination the light arriving at the substrate is after once passing through the photonic chip, back-reflected by the metal layers on top side of the chip. In this configuration a high quantum efficiency with relatively thin absorber layers can be achieved. With an absorber thickness of e.g. 1 µm, values of 0.78 A/W can be reached, but the optical responsivity can be varied over a wide range through the thickness of the Ge layer. Moreover, the bandwidth can be tuned to longer wavelengths by the admixture of Sn in the epitaxy and lastly deep-trench isolation with a depth of 50 µm and a width of 1 µm can be applied to minimize pixel crosstalk (Fig. 3) [7].

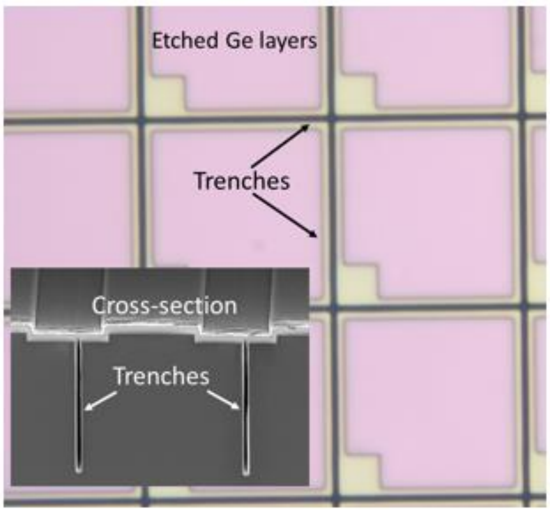

Figure 3 Microscopic view of the deep trench isolation between pixels with a width of 1 µm and a depth of 50 µm

Because the Ge-on-Si detectors deliver the best signal to noise ratio (SNR) under a near zero-volt biasing scheme with the lowest dark current [4], the further designed ROIC needs to provide this special biasing condition besides its main task to acquire and process the photocurrents. Furthermore, with the zero-volt biasing scheme, the leakage current flowing in the shunt resistance of the Ge-on-Si detectors is highly reduced, which also helps to maximize the SNR.

READOUT INTEGRATED CIRCUIT DESIGN

The ROIC can readout 32 Ge-on-Si detectors in parallel, the block diagram in fig. 4 shows an overview of the device. It consists of the 32 direct injection (DI) front-ends for the single Ge-on-Si detectors and a multiplexer with a shift register to control the transfer of the measure data to the output. As described in previous section the Ge-on-Si detector delivers the best SNR at near 0V biasing and to gain from that circumstances, the DI front-ends have the following setup shown in fig. 5.

Two complementary PMOS and NMOS triple cascoded current mirrors force identical currents flowing in the left and right branches. This forces the gate-source voltage of the bottom two n-type MOSFETs to be identical. In this way a very well working near 0V biasing is achieved across the connected Ge-on-Si detectors. Measurements with an Agilent Technologies E5287A SMU verified, that the 0V biasing works quite well. A biasing voltage of less than 2mV is reached which delivers dark currents below the resolvable current step of the ROIC.

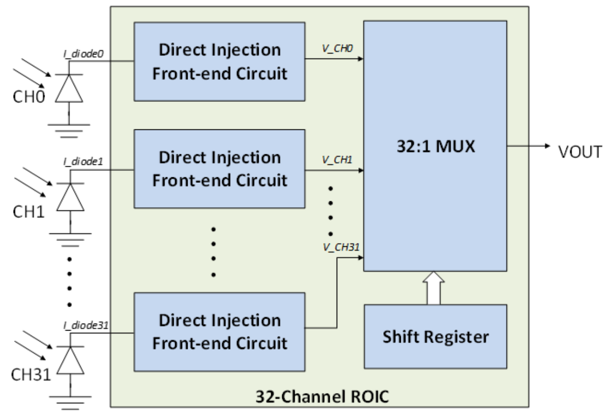

Figure 4 Block diagram of the 32-channel ROIC for the Ge-on-Si detector

In the next stage of the DI front end the detected measure current is converted by an integrated resistor into a linear voltage representing the measure data. The size of the resistor is chosen so that its noise contribution is negligible. In use of the ROIC at 10kHz a SNR of around 45dB with the resistor is gained. This is as well far below the resolvable current step of the ROIC. Clearly this resistor is not a noise contributor for the device.

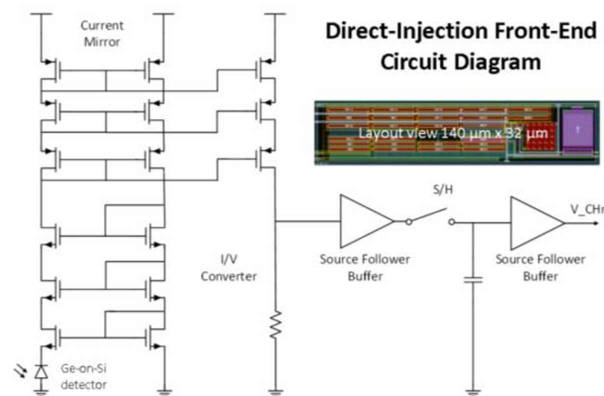

Figure 5 Schematic of the direct injection front-end circuit and the layout view

By a PMOS source follower pre-buffer stage the measured value is passed to a sample & hold (S&H) unit. In the S&H unit a minimum CMOS switch for lowest charge-injection and clock feedthrough error is used. This sample and hold stage can be controlled by an external signal from a microcontroller. Lastly the integrated

Multiplexer takes the data from the 32 channels and controls the release of the measured data to the microcontroller (µC) which is shortly described in the next chapter.

Compared to capacitive transimpedance amplifier (CTIA) based ROICs in [1, 4, 5], the proposed DI current mirror tracks the input photocurrent and no extra bias current is necessary, which leads to an intrinsically ultra-low-power structure. The two source-follower buffers consume only 6 µA current. The ROIC is implemented in XFAB XH018 technology with a supply voltage of 3.3 V 00and occupies 2.25 mm^2 chip area (Fig. 6).

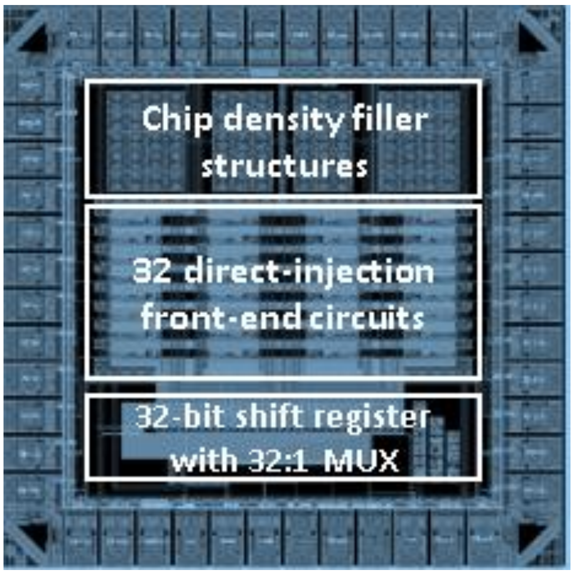

Figure 6 Layout of the fabricated ROIC chip

The ROIC is operated in global-shutter mode and fig. 7 illustrates the output characteristics for various channels of it. It's clearly to see that the channels show linear behavior of the output voltage for different input currents. Input currents from 20 nA to 2 µA can be accurately detected with a 10-bit resolution, i.e. a 2 nA resolvable current step. In consequence the designed ROIC is not limited on the use with the Ge-on-Si detectors, it can also be used for the readout of other devices which need to be biased near zero-volt.

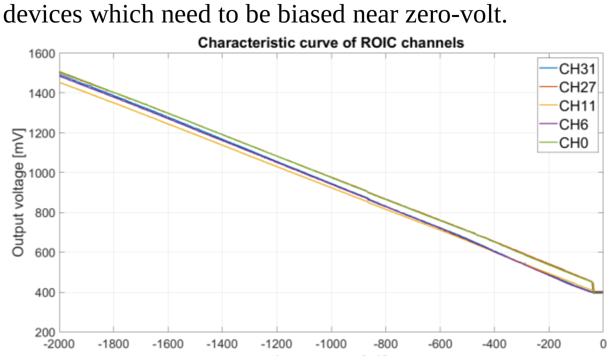

Figure 7 Measured input to output characteristic of several ROIC channels

SOFTWARE

The camera hardware including the ROIC is controlled by a MSP430F5529 microcontroller from Texas Instruments. The running C-software has therefore several tasks:

Firstly the µC needs to control the shift register of the ROIC, so that the measured data from the Ge-on-Si detectors can be transferred. The ROIC is controlled with four signals connected to the µC which brings out several degrees of freedom. For example, an output reset can be performed anytime or the readout speed can be chosen freely. In our camera demonstrator setup a frame rate of 50 fps is realized, which is fast enough to be used for our night vision application. The Ge-on-Si detectors itself can perform up to frequencies greater than 1 GHz and the ROIC also performs well up to 625fps. Therefore, a faster system can be built when necessary.

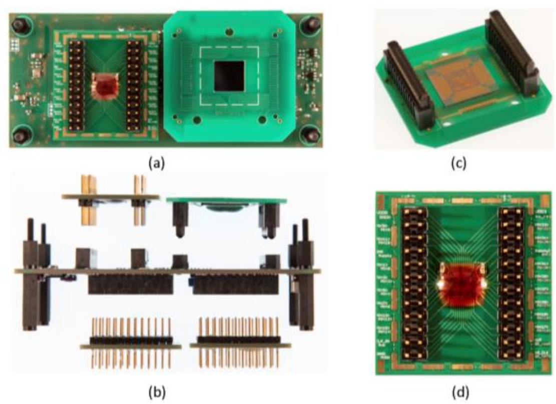

Figure 8 The camera system: (a) Top view of the setup, a window on the detector carrier PCB is used for backside illumination; (b) Side view of the setup with one detector array and three ROICs; (c) Photo of the 10x10 Ge-on-Si detector chip bonded on a carrier PCB; (d) Photo of the ROIC bonded on a carrier PCB

The second task of the µC is to convert the analog measure data to digital values by the integrated 12-bit analog to digital converter (ADC) on the µC. This ADC works according to the SAR (successive approximation register) principle and 12-bit resolution is completely enough, because measure data has only a resolution of 10 bit.

Lastly an USB-interface is used to transfer digital measure data to an external GUI running on a computer. This GUI visualizes measure date and the user has the possibility to trigger measurements as well as doing further control of the camera. For the camera application the GUI continuously polls the measure data from the camera system and visualizes it directly.

MEASUREMENTS

A complete camera system (Fig. 8) is built up combining the 10x10 Ge-on-Si detector array, 3 ROICs to readout 96 of the 100 detectors and a µC integrated on a carrier PCB, which has an advanced grounding concept for optimally separating the analog and digital parts. A low disturbance of the small analog signals can thereby be achieved. As described the outputs of the ROICs are digitized by the µC's 12-bit ADC and an USB is used for data transmission to a GUI. In the experiment, a SuperK-EXTREME laser with a SuperK-SELECT wavelength filter are used to generate a 1310 nm light source. It's coupled into a fiber to illuminate the 10x10 pixel array (Fig. 9a).

In the experiment the fiber is moved from the bottom left corner to the top right corner of the pixel field. This movement is correctly detected by the camera system and displayed in the GUI (Fig. 9b). The functionality of the whole camera system is thereby successfully proven, a distinguishing between non-illuminated and illuminated pixel is clear to see and crosstalk between the pixels is minimized. In fact, this is a good alternative compared to the cost-intensive possibilities like InGaAs.

CONCLUSION

In conclusion a complete Ge-on-Si NIR camera with backside-illumination is described. It consists of a Ge-on-Si detector chip with a high internal quantum efficiency and a fill factor of 74%, a readout integrated circuit with a high dynamic range and a 10-bit resolution, a commercial µC and an USB interface to connect to a computer. By a GUI the measure data is visualized and the camera can be controlled.

With its great results this paper describes a good alternative to the cost-intensive InGaAs detectors inside NIR cameras. In future works a larger number of pixels with the corresponding number of ROIC channels could be used. Also the readout concept can be improved in such a way that readout of even smaller photo currents becomes possible. In doing so a further electronic integration of the ROIC together with photonics could be implemented.

REFERENCES

[1] L. Colace, et al., "A Near-Infrared Digital Camera in Polycrystalline Germanium Integrated on Silicon," in IEEE Journal of Quantum Electronics, vol. 43, no. 4, pp. 311-315, April 2007, doi: 10.1109/JQE.2007.893001.

[2] M. Steglich, et al.; Ge-on-Si photodiode with black silicon boosted responsivity; https://doi.org/10.1063/1.4927836.

[3] L. Colace and G. Assanto, "Germanium on Silicon for Near-Infrared Light Sensing," in IEEE Photonics Journal, vol. 1, no. 2, pp. 69-79, Aug. 2009, doi: 10.1109/JPHOT.2009.2025516.

[4] A. Köllner, et al., "A 2x2 Pixel Array Camera based on a Backside Illuminated Ge-on-Si Photodetector," 2019 IEEE SENSORS, Montreal, QC, Canada, 2019, pp. 1-4, doi: 10.1109/SENSORS43011.2019.8956731.

[5] R. Kaufmann, et al., “Near infrared image sensor with integrated germanium photodiodes.” Journal of Applied Physics, vol. 110, no. 2, p. 023107, 2011.

[6] J. Michel, J. Liu, L. C. Kimerling, “High-performance Ge-on-Si photodetectors”, Nature Photon., vol. 4, no. 8, pp. 527-534, Jul. 2010.

[7] M. Oehme, et al., "Backside Illuminated “Ge-on-Si” NIR Camera," in IEEE Sensors Journal, doi: 10.1109/JSEN.2021.3091203.

This work is funded by the German Federal Ministry of Education and Research (BMBF) as part of "Nachtsichtkamera für Automotiv-Anwendungen" NASIKA project, contract numbers 03VP00411 and 03VP00412.

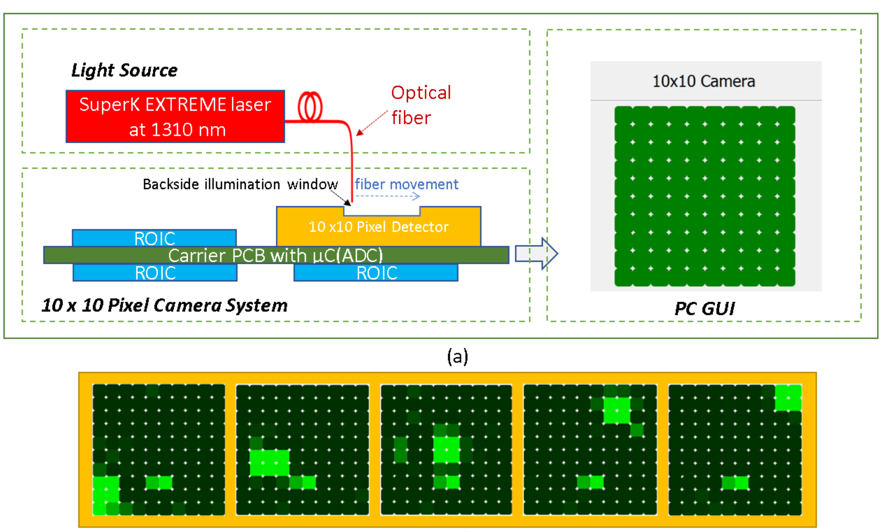

Figure 9 Experiments with the camera system: (a) illustration of the measurement setup; (b) Detected movements of the fiber from the bottom left corner to the top right corner.