Ge/Si Electrically Tunable VIS/SWIR Photodetector

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We report on a epitaxial Ge-on-Si dual-band photodetector grown on a Si p-n junction, to form two photodiodes connected in a back-to-back configuration. The device responsivity can be tuned, with an external bias, to cover wavelengths within the visible and near-infrared spectral regions.
Keywords: *Ge epitaxy, Ge-on-Si photodetectors, dual band.*

INTRODUCTION

This Ge-on-Si photodiodes have been firstly reported more than twenty years ago [1] opening the way for the integration of IR photodetectors on Si. A tremendous development has been done, moving from vertically illuminated, stand-alone devices, to waveguide integrated arrays of photodetectors [2] and CMOS integrated imagers [3]. Usually, the Ge epilayer act as the absorbing material for the SWIR radiation, while Si acts only as a substrate. Here we report on a dual-band Ge-on-Si photodetector where light detection can take place both within the Ge epilayer and the underlying Si substrate: the device responsivity can thus be tuned from the VIS to the SWIR spectral range by means of an external bias. Therefore, the presented device can be implemented as a VIR-NIR-SWIR CMOS compatible imager.

WORKING PRINCIPLE AND DESIGN

A schematic representation of the dual-band photodetector is shown in in Fig. 1. Two photodiodes in a back-to-back configuration are formed by p-doping the back side of a high resistivity Si wafer and by epitaxially growing a p-i-n heterojunction Ge-on-Si layer on the front side (Fig. 1a)). An external bias can be applied to the whole layer stack be means of ohmic contacts formed on the top Ge layer and on the wafer backside (see Fig. 1b)). When a positive bias is applied between the top and bottom contact, the Ge diode is forward biased while the Si diode is reversed biased. In such a configuration the photocurrent generated within the Si substrate by back illuminating the device, will flow through the external circuit and be detected. By reversing the bias polarity, still maintaining a backside illumination, the detected photocurrent will be that generated within the Ge epilayer: in this way it is possible to tune the device responsivity simply by controlling the external bias.

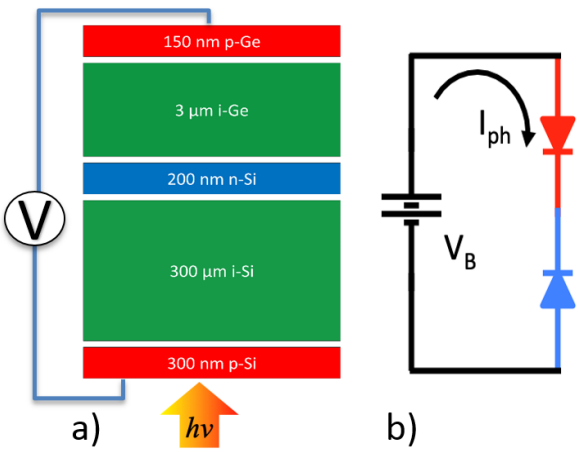

Figure 1: a) Schematic representation of the layer stack resulting in a Si p-n junction and and Ge-on-Si p-i-n junction connected back to back as sketched in panel b).

EPITAXIAL GROWTH AND DEVICE FABRICATION

A TCAD model has been set up to optimize doping levels, in particular that of the Si substrate, determining the most effective position the p-n junction within the Si photodiode (at the bottom surface or at the Ge/Si interface) and investigate the role played by substrate thickness [4]. The layer stack reported in Fig. 1a) represents the outcome of such optimization procedure. A p-type layer has been formed on the backside of an intrinsic Si wafer by spin-on-dopant obtaining a boron-doped layer with an average concentration of 2×1019 cm-3 and a thickness of ≈300 nm. The epitaxial growth has been performed by low-energy plasma-enhanced chemical vapor deposition (LEPECVD)[6]. Firstly a 200 nm thick phosphorous-doped Si layer has been deposited at 760°C followed by 3 µm thick nominally undoped Ge, grown at 500°C. Six thermal annealing cycles have been performed in-situ to reduce threading dislocation density. As a final step 150 nm of boron-doped Ge have been deposited.

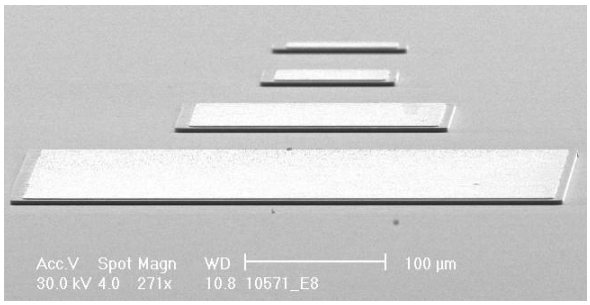

Figure 2: SEM view of the Ge mesa and top contact.

Prior to fabrication the Si wafer has been diced into square 1×1 cm2 chips. Square mesas with dimensions ranging between 100-500 µm have been realized by standard UV lithography and dry etching on the Ge-on-Si epitaxial layer. The mesas have been etched down to the intrinsic Si surface to electrically isolate the different devices on the same chip. The top ohmic contacts have been realized by e-beam deposition of a Ti/Al metal stack (100 nm Ti and 1000 nm Al) and lift-off. The bottom ohmic contact has been fabricated by depositing two rectangular stripes of Ti/Au (10 nm Ti, 150 nm of Au) on the backside of the chip. An SEM image of the fabricated device is shown in Fig. 2.

DEVICE CHARACTERIZATION

Optical characterization was performed by means of lamp-monochromator set-up. The bias dependent dual-band operation of the device is demonstrated in Fig. 3, where the spectral responsivity is shown for two different applied voltages. The VIS/NIR operation of the device is clearly demonstrated. For V_B = +1 V, the Si photodiode is reverse biased giving a photoresponse in the 400-1200 nm spectral range. When the bias voltage is reversed to V_B = -1 V, the Ge photodiode is reverse biased and a photoresponse in the 1000-1650 nm spectral range is obtained. Its short wavelength cut-off is due to the absorption of Si.

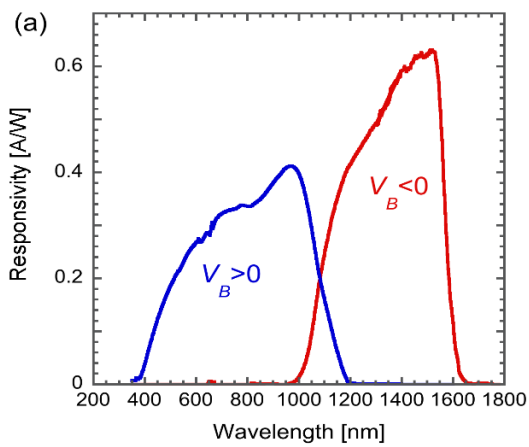

Figure 3: Spectral responses measured at VB = +1V (blue) and at VB = -1V (red).

The peak responsivities of the two bands are 0.41 A/W and 0.63 A/W at 960nm and 1520 nm, respectively. The overall performance of a photodetector has been evaluated by estimating the specific detectivity D* of the device, which, thanks to its low voltage operation has been found to be $7{\cdot}10^{11}$cmHz$^{1/2}$/W and $2{\cdot}10^{10}$cmHz$^{1/2}$/W in the VIS and NIR, respectively [7].

VIS-NIR single-pixel imaging was performed by mounting the chip on a rastering system comprising a three-axis stage. In this way the pixel can scan the image plane behind a piano-convex lens. Two images, one in the VIS and one in the NIR, can be obtained by repeating the scanning and changing the polarity of the applied bias at the device. A coloured VIS image has been obtained by repeating the measurements three times with three different optical bandpass filters (450nm, 550nm and 650nm) resulting in three images with R, G, and B components, which have been combined to obtain the final VIS image.

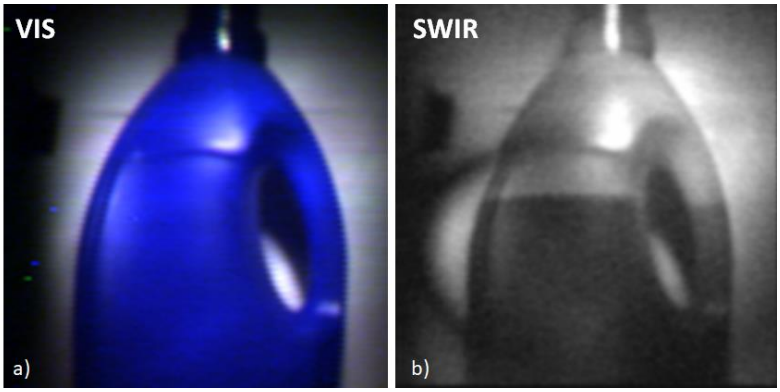

Figure 4 Images obtained with the rastering system a) RGB image obtained with the Si part of the device and b) SWIR image obtained with te Ge part of the device.

CONCLUSION

In conclusion, we have designed and fabricated a voltage-tunable dual-band photodetector operating in the VIS and NIR range. The device is based on a couple of p-i-n photodiodes connected back-to-back formed within a Ge-on-Si epitaxial structure. The device operates between 400 and 1600 nm and its architecture enable to electronically select the shorter (400-1100 nm) or longer (1000-1600 nm) wavelength range with a relatively low applied voltage. VIS-NIR single-pixel imaging has been performed.

ACKNOWLEDGMENT

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