Back-illuminated normal-incidence Ge-on-Si photodetectors

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ABSTRACT

Backside illumination enables an increase in photoactive area and numerical aperture of Ge-on-Si photodetectors for SWIR applications. The transparency of silicon in the infrared range ($\lambda > 1.1$ µm) allows a nearly lossless propagation of incoming light through the Si substrate and also an application of optical microstructures on the rear side of the Si substrate. Moreover, an aluminium front contact covering the whole top area serves as a mirror which extends the optical propagation of the detectable SWIR light through the absorbing layers and hence increases the quantum efficiency. We developed back-illuminated Ge-on-Si photodiodes to verify these concepts. Especially the usage of light trapping structures shows great potential. Among the different microstructures we chose black silicon (b-Si) as a promising light trapping candidate. After the fabrication, photodiodes with different configurations were evaluated. The obtained results show a strong increase of the quantum efficiency due to both, the existence of an Al mirror and the application of b-Si.

Keywords: Ge-on-Si, pin-photodiode, Backside illumination, SWIR, Microstructures, Black silicon

1. INTRODUCTION

According to many investigations in the field of thin-film technology, by now it is possible to implement almost every common infrared photodetection material on silicon substrates [1]-[6]. Front-illuminated sensors usually suffer from area limitations due to the presence of electronic circuits. Moreover, incoming light has to pass through multiple layers of metal and dielectrica which causes reflection, deflection and absorption losses. Hence, the substantial advantage of backside illumination is an increase in photo-active area and numerical aperture. Yet, VIS back-illuminated photodetector chips need to be back-thinned to a thickness of only a few microns to reduce absorption losses within the substrate. This drawback is no longer existent for short wavelength infrared (SWIR) photodetectors thanks to the transparency of the silicon substrate in the SWIR range. Incoming light propagates without extinction towards the front side where the detection material is located. The silicon substrate even serves as an optical longpass filter due to its transparency only for wavelengths greater than 1.1 µm.

Furthermore, this enables the application of micro- and nanostructures on the backside, such as polarizers, diffraction gratings, computer generated holograms (CGHs), antireflection structures or plasmonic structures which can improve the performance of the photodetector or, alternatively, may be used for sophisticated metrology applications.

2. FABRICATION OF GE-ON-SI PHOTODIODES

In order to investigate the feasibility of back-illuminated, Si-based SWIR photodetectors, we established a process chain to manufacture vertical Ge-on-Si photodiodes, starting from an epitaxial layer stack (Fig. 1a) grown by molecular beam epitaxy (MBE). This process chain has been extensively tested and first Ge-on-Si photodiodes have eventually been produced (Fig. 1b). Ge-on-Si photodiodes can efficiently detect light up to a wavelength of 1550 nm which corresponds to the direct bandgap of germanium [1],[2]. Further detection materials, such as GeSn alloys [3], InGaAs [4], 2D materials [5] or HgCdTe [6] on Si wafers are also conceivable.

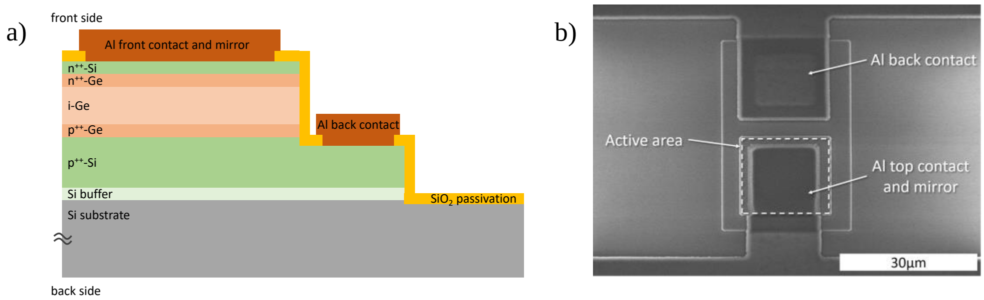

Figure 1. (a) Design of a vertical Ge-on-Si photodiode. (b) SEM picture of a manufactured Ge-on-Si photodiode (top view).

Fig. 1a shows the design of the photodiodes consisting of a double mesa structure with a vertical p-i-n doping profile. The p- and n-layers, with a thickness of 100 nm each, are relatively highly B- respectively Sb-doped of about 10^{20}cm^{-3}. This enables a strong built-in electrical field and a depletion region that spans the entire intrinsic layer. The latter implies that these devices are able to generate an inherently high photocurrent even in zero bias operation (photovoltaic mode). While the whole germanium region is light absorbing, only the absorbed photons within the intrinsic layer account for the photocurrent. Photocarriers generated within the doped areas are not collected due to high Auger recombination in conjunction with slow carrier diffusion. For an intrinsic layer of 300 nm and a total Ge layer thickness of 500 nm, this results in an internal collection efficiency of about 60%.

For a front side illuminated photodiode, the top contact can only cover the peripheral area due to the need of an illumination window. On the contrary, in backside illumination configuration, the 500 nm thick Al top contact metallization covers the whole photoactive area. Upon illumination from the rear, the aluminium acts as a mirror with a reflectivity of more than 91%, thus extending the optical path length through the Ge diode and almost doubling the absorption and respectively the quantum efficiency, within one passage through the photodiode. The buried layer contact is connected via the lower mesa level. It consists of a 400 nm thick B-doped Si.

We produced photodiodes with active areas from 20 µm to 500 µm width and a differing Al top contact covering in one case the whole area and in the other only the peripheral area leaving an open illumination window for front side illumination. The 250 nm thick SiO2 passivation layer is a λ/4-coating for a wavelength of 1500 nm and hence serves as an antireflection layer. The photodiodes were characterized over a wavelength range from 1440 nm to 1640 nm using a tunable, fiber-coupled laser AQ2200-136 by Yokogawa and a source measure unit (SMU) 2601 by Keithley. The laser is collimated and subsequently focused through the backside of the substrate on the front side located photodiodes. A numerical aperture of 0.13 results in relatively small propagation angles around 2° within the Si substrate. For the Al mirror configuration, this leads to several transits of the propagating light through the photodiode due to reflections on the Al mirror and the rear side surface. Calculating these reflections, with reflectivities of 91% between Si and Al and 31% between Si and Air, results in an absorption enhancement factor of approximately 2.5 compared to the configuration without Al mirror. The measurements displayed in Fig. 2 validate this enhancement factor. The dashed line indicates the measurements of the configuration without Al mirror multiplied by 2.5. A photodiode with a relatively large active area of 200 µm width was surveyed. For smaller areas and higher numerical apertures, this consideration may not be valid albeit.

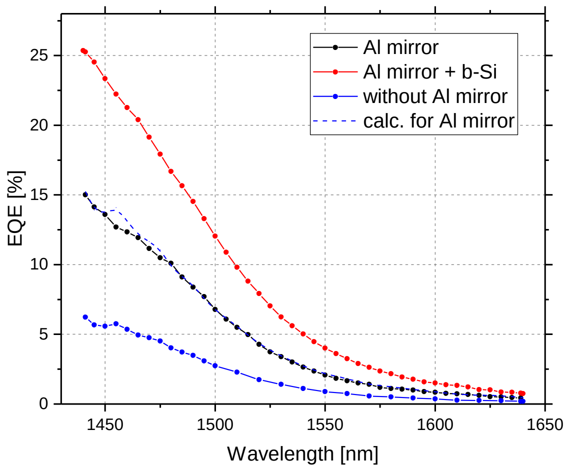

Figure 2. Measured external quantum efficiency (EQE) spectra of Ge-on-Si photodiodes with a lateral active area of 200 x 200µm² each. Configurations with and without an aluminium mirror are compared. Additionally, measurements of a chip with Al mirror configuration and black silicon (b-Si) microstructures are displayed.

Already at 1440nm, the spectrum shows a quickly descending external quantum efficiency (EQE) towards higher wavelengths while the band gap of germanium would be expected at 1550 nm. This can be explained by compressive strain within the epitaxial layers. The thermal expansion coefficient of germanium is larger compared to silicon. After the epitaxial growth at high temperatures; the layers cool down and thus a compressive strain is induced. Compressive strain modifies the band structure and shifts the band gap towards smaller wavelengths [1],[7]. Applying an additional relaxation step during the epitaxial growth process can turn this effect from compressive to tensile strain and extend the absorption spectrum to higher wavelengths instead [1],[2],[7]. However, this fact is not essential for the presentation of our principle results.

3. MICROSTRUCTURING THE BACKSIDE

After front side processing, we can also fabricate a designated microstructure on the silicon rear side of the photodetector. For example, scattering microstructures can be used to 'trap' the light inside the detector and thus increase the light absorption [8] and quantum efficiency [2],[9], respectively.

One approach comprises the application of stochastic needle-like structures, called black silicon (b-Si) shown in Fig. 3a. Besides its antireflection effect, it induces a transmissive scattering with a broad angular spectrum when coupling the incoming light through the b-Si structure. A great amount of light is scattered into angles above the angle of total reflection (~17°) which hinders the light from leaving the chip again. Thus, the absorption can be increased significantly by a factor of 3 to 5 depending on the present layer thickness and wavelength [2],[9].

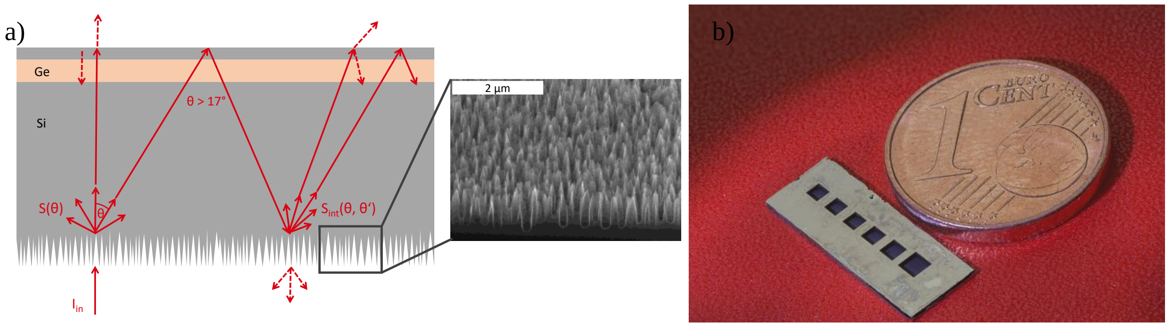

Figure 3. (a) Scheme of light trapping with b-Si. (b) Locally back-thinned and b-Si-structured rear side of Ge-on-Si photodiodes.

The advantage of b-Si over other microstructures is its simple and cost-efficient stochastic formation which does not require any lithographic technology. However, other microstructures could be more precisely adapted to the exact specifications of the particular device. Possible light trapping structures comprise plasmonic structures, diffraction gratings or CGHs [10].

The application of such structures makes further considerations necessary. The principle of light trapping is based on scattering or diffraction of incoming light into higher angles. While this increases the overall optical absorption for large area photodiodes, smaller photodiodes are easily missed by the scattered rays, thus causing signal reduction or optical crosstalk and blurring (in the case of sensor arrays). To ensure the propagation of light into the desired photodiodes two options are conceivable: either a local backside etch or an optical separation of the individual sensor pixels by deep narrow trenches. A local backside etch appears to be the rather viable option. For now, the etching was done by ICP-RIE (inductively coupled plasma – reactive ion etching) dry etching. The chips were back-thinned to a residual thickness of 50 µm which is sufficiently thin for devices with lateral dimensions > 100 µm. Subsequently a b-Si structure was fabricated within the etched indentation (see Fig. 3b). The measurements of these devices showed a significant improvement of the EQE presented in Fig. 2.

4. CONCLUSIONS

In conclusion, the presented investigations prove the feasibility of the concept of a back-illuminated Ge-on-Si photodiode. Backside illumination in combination with metallic front reflectors can significantly enhance the quantum efficiency of Ge-on-Si photodiodes. In addition, it gives the opportunity for the application of sophisticated microstructures such as diffraction gratings, wire grid polarizers or light-trapping structures. As example, we demonstrated a further increase in quantum efficiency by applying a b-Si light-trapping structure to back-thinned Ge-on-Si photodiodes. Generally, backside illumination opens a pathway towards efficiency enhancements and sophisticated, integrated sensor solutions.

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