Si-microstructures for back-illuminated Ge-on-Si photodetectors

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Back-illuminated Ge-on-Si photodiodes enable the interaction of incident light with micro- and nanostructures applied on the rear side. Especially light trapping structures offer great potential as they can significantly improve the quantum efficiency of the photodiodes located at the front. We demonstrate this phenomenon by using black silicon nanostructures.

1 Introduction

Photodetectors have become an indispensable part of a multitude of technological applications. Silicon photodetectors in particular, which cover a detection range down to wavelengths of approx. 1 µm, have benefited enormously from the constantly advancing development in semiconductor technology. Photodetectors in the infrared range (IR) for wavelengths > 1 µm were only able to keep up with this trend to a limited extent. There are two reasons for this. The materials used are expensive to manufacture and process. In addition, such detectors consist of several chips, i.e. at least a detector chip and a readout chip, which necessitates a complex connection, for example by flip-chip bonding or wire bonding. At the same time, there is an enormous interest in applications such as automotive/LiDAR, food technology, recycling, quality control or hyperspectral observation.

The integration of IR absorption materials on Si-platforms has a great potential in terms of cost and material savings and thus opens up this technology for consumer applications. A high level of integration and size reduction also enables the development of novel sensors and endoscopic applications. One example of such integration is Ge-on-Si technology [1]. Nonetheless, there is a whole range of other possible materials to be integrated, such as III-V semiconductors [2], 2D materials [3] or PbS quantum dots [4].

2 Light trapping for efficiency enhancement

However, all integrated materials are limited in their layer thickness, resulting in relatively low absorptions and correspondingly low quantum efficiencies. One of our goals is therefore to improve quantum efficiency using micro- and nanostructures.

One advantage is the nearly perfect transparency of Si substrates for wavelengths above 1.1 µm. This makes it relatively easy to implement backside illumination of the photodetector, thus increasing the active area and providing more space for sophisticated readout electronics. Light incident from the rear interacts with the microstructures located there and propagates loss-free through the substrate to the photodetector located at the front. In addition, the Si substrate serves as a long-pass filter by absorbing all short-wave light below 1.1 µm.

So-called light trapping structures [5] can be used to increase quantum efficiency. A well-known representative is black silicon (b-Si) [6]. It consists of needle-like randomly distributed structures with lateral dimensions of a few hundred nanometers (see Fig. 1). Due to a vertically continuously increasing material density, the refractive index also changes continuously with increasing depth. This prevents Fresnel reflections and creates an anti-reflection effect.

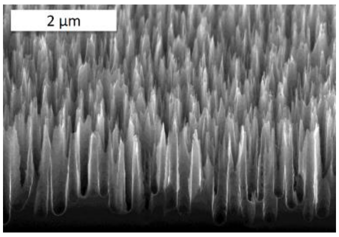

Fig. 1 *SEM image (oblique view) of b-Si nanostructures.*

In addition, it generates a broad transmissive scattering into the Si substrate (see Fig. 2). This extends the optical path of the light through the substrate as well as through the detector layer, which effectively increases the absorption and thus the quantum efficiency of the photodetector [6].

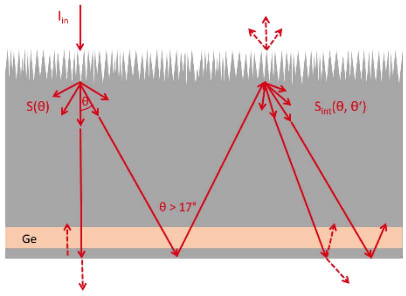

Fig. 2 *Principle of light trapping by b-Si nanostructures in a Si substrate with an inserted absorption layer of Ge.*

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3 Black silicon on Ge-on-Si photodiodes

To investigate this phenomenon we produced Ge-on-Si PIN photodiodes. These were fabricated as double mesa structures from epitaxial layer stacks with a vertical PIN doping profile (see Fig. 3). This structure allows a coupling of light under normal incidence and thus makes an arrangement of photodiode arrays possible.

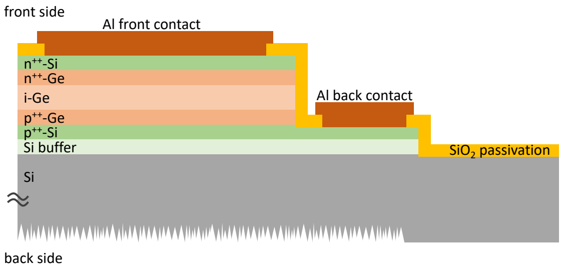

Fig. 3 *Schematic of a Ge-on-Si photodiode (not drawn to scale).*

However, the broad scattering on which light trapping is based also causes the light to scatter past the intended pixel, also known as optical crosstalk. There are two ways to prevent optical crosstalk. On the one hand, the insertion of optical trenches causes light guidance to the designated pixel. On the other hand, a (local) thinning of the substrate reduces the crosstalk (see Fig. 4).

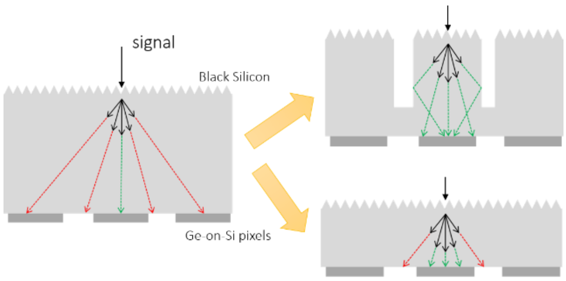

Fig. 4 *Reducing optical crosstalk by trenching or (local) back thinning.*

Measurements of the external quantum efficiency (EQE) of Ge-on-Si photodiodes show promising enhancement factors (see Fig. 5).

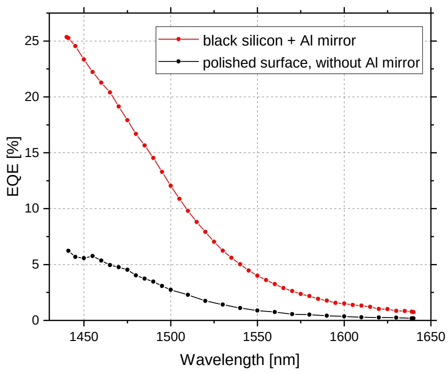

Fig. 5 *Comparison of two back-illuminated Ge-on-Si photodiodes, one with b-Si structure and with an Al contact serving as retroreflector, the other without.*

b-Si is particularly well applicable, since no lithography is needed for the production and it works in a broadband spectral range. However, other micro- and nanostructures could be adapted more precisely to the specific application, wavelength and dimensions of the photodiodes. The use of suitable diffraction gratings [7], plasmonic structures [8] or computer-generated holograms is conceivable.

4 Conclusion and outlook

The principle of backside illumination of IR photodetectors on a Si platform allows the application of desired nanostructures on the Si backside. This was successfully demonstrated by back-illuminated Ge-on-Si photodiodes in combination with black silicon light trapping structures.

In addition to the use of light-trapping structures, illumination via the free rear side of the Si substrate offers a wide range of possible applications. Wire-grid polarizers [9] or wave plates [10][9] enable the miniaturization of polarization-based measurement methods in the IR range. The spectral separation of incident light by diffraction gratings could be used for the development of integrated spectroscopic applications. Many integrated solutions and new sensor concepts seem conceivable with this principle.

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