Thin film InGaAs MSM photodetectors integrated onto silicon-on-insulator waveguide circuits

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Silicon-on-insulator (SOI) is rapidly emerging as a versatile platform for a variety of integrated nanophotonic components. High density waveguide circuits can be fabricated using standard CMOS processing techniques. However, light detection in the near-infrared wavelength range (1550 nm) is not possible in silicon which is naturally transparent in this region. One possibility for overcoming this is the integration of III-V semiconductors. We present simulation results of a very compact thin film InGaAs metal-semiconductor-metal (MSM) detector integrated on an SOI waveguide. These photodetectors can be fabricated on a wafer scale and efficiencies of +90% are predicted for wavelengths up to 1650 nm.

Introduction

The SOI material system possesses unique optical properties due to the large refractive index difference between silicon (n = 3.45) and silica (n = 1.45). This allows the creation of very compact and high density waveguide circuits including so-called photonic wires with bend radii as small as 1 µm [1] and photonic crystals. Moreover, these waveguide structures can be fabricated on a wafer scale using standard CMOS processing techniques, including deep ultraviolet lithography [2]. Keeping in mind the worldwide silicon fabrication infrastructure available, it is clear that this evolution could revolutionize the photonics industry [3]. As silicon is transparent for wavelengths above 1.1 µm, photodetection at wavelengths typically used for optical communications is not possible in silicon. One possibility for overcoming this problem is epitaxial growth of germanium on top of silicon waveguides [4]. Another possibility is the heterogeneous integration of thin film III-V compound semiconductors. We believe that this approach can lead to higher performances: InGaAs has an unchallenged position in low dark current, high speed and high sensitivity integrated near-infrared photodetectors. On top of that, for the fabrication of SOI waveguide integrated laser diodes [5], integration of III-V material is the only viable solution and detectors and sources could be fabricated in the same processing steps, using the same wafer scale III-V technologies.

Thin film heterogeneous integration

This integration approach consists of bonding multiple unprocessed III-V dies (epitaxial layers down) onto a processed SOI wafer using a polymer, BCB as a bonding agent. After bonding, the III-V substrate is removed leaving unprocessed epitaxial III-V layers bonded onto the SOI waveguide substrate. From now on, photodetectors can be processed on a wafer scale. This adhesive die-to-wafer bonding approach is clearly described elsewhere [5]. The main advantage as compared to other hybrid integration techniques is that it allows processing the InGaAs photodetectors on a wafer scale.

Photodetector design

We previously reported two types of integrated p-i-n photodetectors based on the same thin film heterogeneous integration technique [5,6]. The advantages of the detector design discussed in this paper are its high theoretical quantum efficiency, large spectral bandwidth, easy processing and compact size.

The design we propose in this paper is based on the principle of coupled mode theory. By using a thin BCB bonding layer (~200 nm) in between the SOI waveguide and detector and by proper design to obtain phase-matching between the optical mode in the SOI waveguide and the detector waveguide mode, optical coupling between guide and detector will occur. A schematic picture of the design is shown in figure 1(a), a cross-section view in figure 1(b).

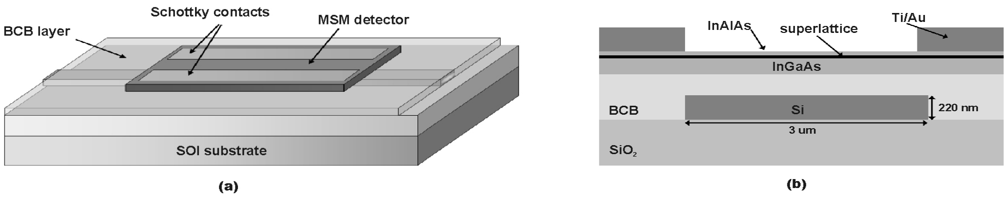


Fig. 1(a). Schematic- and (b) cross-section view of waveguide integrated MSM detector

The material structure of the thin film MSM detector consists of a 40 nm InAlAs Schottky barrier enhancement layer, 20 nm InAlAs/InGaAs superlattice layer to decrease carrier trapping by the bandgap discontinuity between $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ and a 145 nm $In_{0.53}Ga_{0.47}As$ absorption layer. All layers are not intentionally doped and lattice matched to the InP substrate. Two Schottky electrodes (Ti/Au, 20nm/200nm) are deposited on top, with the same spacing as the SOI waveguide as can be seen in figure 1. Lateral confinement of the detector waveguide mode is obtained by the two Ti/Au Schottky electrodes. The large imaginary part of the refractive indices of Ti (4.62) and Au (9.81) at 1.55 µm lowers the effective refractive index of the fundamental slab mode of slices A as compared to slice B and this causes lateral confinement as can be seen in figure 2(b). As a consequence, absorption loss in the Ti/Au electrodes is small as will be calculated in this paragraph and on top of that, no waveguide ridge has to be defined, strongly simplifying the processing.

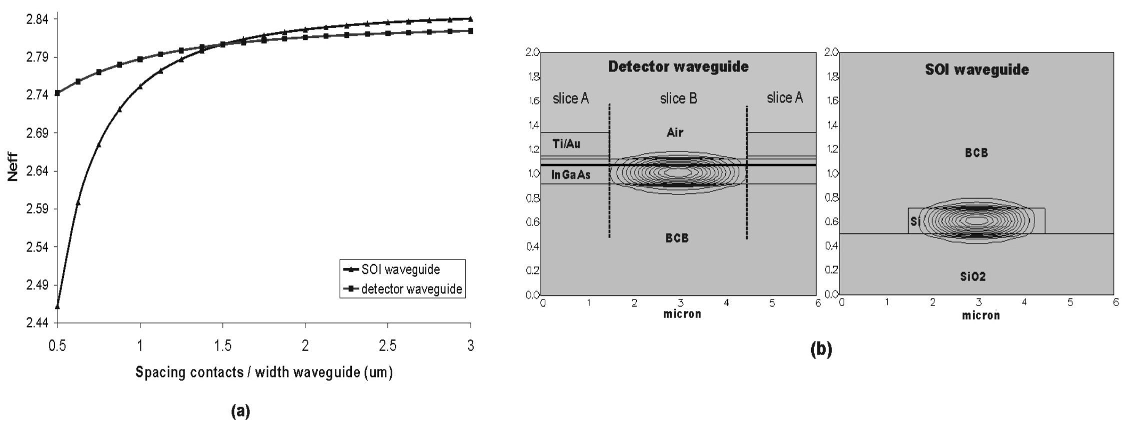
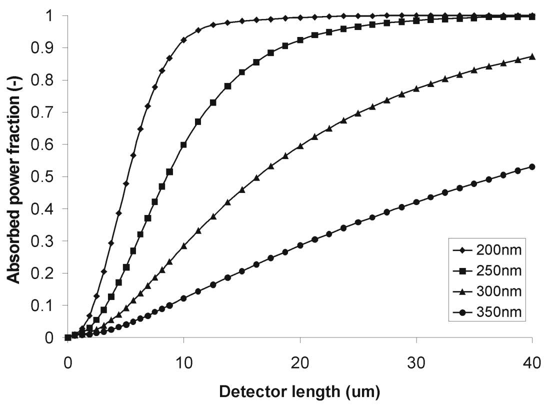


Fig. 2 (a) Real part of the effective refractive index of the TE ground modes of the decoupled detector waveguide and decoupled SOI waveguide in function of contact spacing and waveguide width respectively and (b) corresponding mode profiles.

Figure 2(a) shows the (real part of the) effective refractive index (N_{eff}) of the TE ground modes of the decoupled detector- and SOI waveguide in function of respectively Schottky contact spacing and waveguide width. Corresponding mode profiles are shown in figure 2(b). Using deep-UV lithography, contact spacings down to 200 nm are easily obtainable but here we limited ourselves to 1 µm, which is compatible with standard optical contact lithography. Phase-mismatch of the decoupled waveguide modes smaller than 1.3 % can be obtained with spacings/widths from 1 µm to 3 µm using the layer structure described above. As absorption resonances occur when the (real) propagation constants of the fundamental modes of the decoupled waveguides coincide, the smaller the phase-mismatch, the higher the detector absorption per unity of length. A fully vectorial 3D simulation tool based on eigenmode expansion has been used to calculate the absorbed power as a function of the detector length (figure 3). The simulated structure has a contact spacing and waveguide width of 3 µm. When having a 200 nm thick BCB bonding layer between the SOI waveguide and the detector, 95% of the power is absorbed for detector lengths as short as 11 µm. It is well know from coupled mode theory that when the spacing between the two waveguides increases, couple length will increase. As a consequence of that, the detector efficiency for a given length will decrease for increasing bonding layer thickness as can be seen in figure 3.



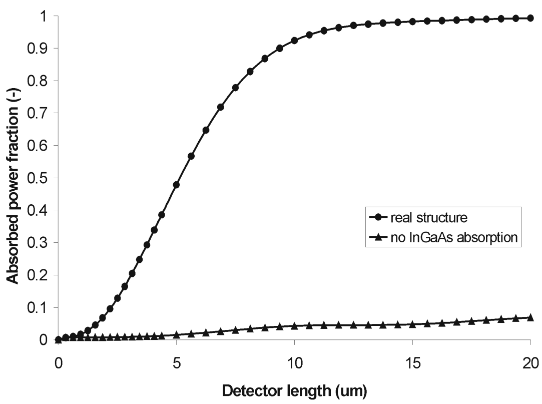


Fig. 3. (Left) Absorption as a function of detector length for different bonding layer thicknesses.
Fig 4. (Right) Influence of optical absorption in the Schottky contacts (Ti/Au).

To estimate the loss due to absorption in the Ti/Au Schottky contacts, we calculated the absorbed power as a function of detector length for both the real structure and the structure where we do only take into account absorption in the Schottky contacts and no absorption in the InGaAs layers. However, this is an approximation because setting the imaginary part of the refractive index of InGaAs to zero slightly influences the field profile. The results are shown in figure 4. When we only consider absorption in the Schottky contacts, power in the structure is lost, but at a very slow pace. From this approximated method, we can conclude that loss due to absorption in the Schottky contacts is limited (smaller than 10% of input power). This is caused by the fact that the contacts are used to obtain lateral waveguide confinement as explained earlier.

In figure 5, the absorbed power as a function of the wavelength is shown for detectors with a length of 10, 20 and 50 µm and with a 3 µm wide detector- and SOI waveguide. Dispersion relations of all the materials were taken into account in this simulation;

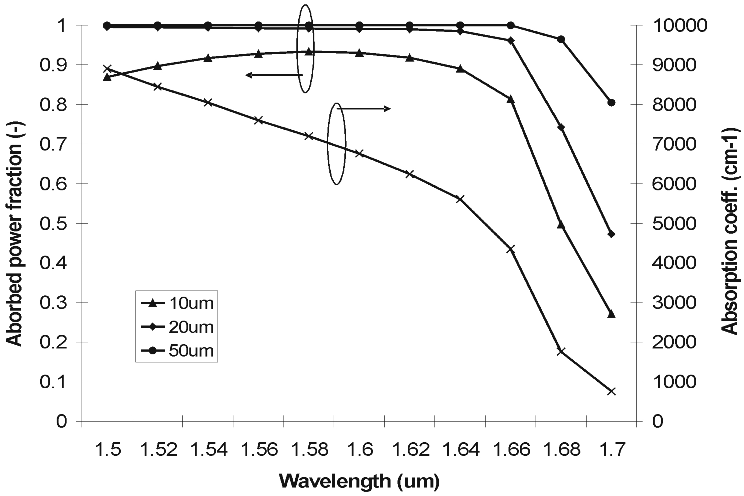


Fig. 5. Absorption coefficient of InGaAs and spectral bandwidth of the MSM detector, parameter is detector length.

however the main contribution is due to the lower absorption coefficient of InGaAs at larger wavelengths as can be seen in the figure. There is a sharp drop in absorbed power around 1.65 µm, which corresponds with the bandgap of InGaAs lattice matched to InP. By increasing the detector length the spectral bandwidth can be improved, however, detector capacitance and dark current will rise.

Conclusion and acknowledgement

We presented the design of an InGaAs MSM detector integrated on a silicon-on-insulator platform. It was shown that an internal quantum efficiency of more than 90% can be achieved for a 15 µm long device and a 200nm intermediate BCB bonding layer. The ultra-compact device offers a high spectral bandwidth and a very simple processing. By tuning the detector length or bonding layer thickness, a fraction of the optical power can be detected for power monitor applications.

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References

[1] P. Dumon et al., "Basic photonic wire components in silicon-on-insulator", in Proceedings of the 2nd IEEE International Conference on GroupIV Photonics, 2005, pp. 189-191.

[2] W. Bogaerts et al., "Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology", Journal of Lightwave Technology, vol. 23, pp. 401-412, 2005.

[3] R. Baets et al., "Silicon-on-insulator based nano-photonics: Why, How, What for?", in Proceedings of the 2nd IEEE International Conference on GroupIV Photonics, 2005, pp. 168-170.

[4] J. F. Liu et al., "Waveguide-Integrated Ge p-i-n Photodetectors on SOI platform", in Proceedings of the 3rd IEEE International Conference on GroupIV Photonics , 2006, pp. 173-175.

[5] G. Roelkens et al., "Laser emission and photodetection in an InP/InGaAsP layer integrated on and coupled to a Silicon-on-Insulator waveguide circuit", Optics Express, vol. 14, pp. 8154-8159, 2006.

[6] G. Roelkens et al., "Integration of InP/InGaAsP photodetectors onto Silicon-on-Insulator waveguide circuits", Optics Express, vol. 13, pp. 10102-10108, 2005.