INVESTIGATION OF EVANESCENT COUPLING BETWEEN SOI WAVEGUIDES AND HETEROGENEOUSLY-INTEGRATED III-V PIN PHOTODETECTORS

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Abstract

Integrating III-V materials on Si is a promising candidate to realize both passive and active optical functions on a single silicon chip. We have developed this heterogeneous integration technology by means of an adhesive die-to-wafer bonding process under a low temperature. In this paper, efficient evanescent coupling between SOI waveguides and heterogeneously-integrated III-V pin photodetectors is proposed. The serious absorption by p-InGaAs and metal contact layers are greatly reduced by introducing a central opening on these layers. The thickness of the i-InGaAs layer is also optimized towards efficient absorption.

I. Introduction

SOI (silicon-on-insulator) photonic wire waveguides with ultra-high refractive index contrast are becoming more and more attractive [1, 2]. By using SOI photonic wire waveguides, it is possible to have a submicron cross section, an ultra-small bending radius, a very small decoupled separation and consequently a very high integration density.

However, due to intrinsic material limitations, Si is outperformed by III–V semiconductor materials for active functionalities, such as light generation and detection at telecom wavelengths (1.31~1.55μm). These III–V materials can be heterogeneously integrated on an SOI wafer by means of a low-temperature die-to-wafer bonding process with divinyldisiloxane benzocyclobutene (DVS-BCB) as the bonding layer [3]. The bonding process consists of bonding unprocessed III-V dies (epitaxial layers down) onto a processed SOI substrate, removal of the III-V substrate through a combination of mechanical grinding and chemical etching, and subsequent wafer-scale processes to fabricate the III-V devices and lithographically align them to the underlying SOI waveguides. Hereby, various active components such as lasers [4] and photodetectors [5], have been demonstrated based on this platform.

We have reported III-V pin photodetectors integrated on Si with the help of a grating coupler to diffract the light from SOI waveguides vertically to photodetectors [5]. However, like ordinary surface-illuminated detectors, there is a trade-off between the responsivity and the transition-time-limited bandwidth when choosing the thickness of the intrinsic InGaAs (i-InGaAs) absorption layer [6]. Furthermore, the responsivity is inevitably limited by the efficiency of the grating coupler, which is normally less than 40% [7].

Since an ultra-thin bonding layer (~100nm) [8] has been technically achieved, an evanescent coupling scheme can be adopted to couple the light from the SOI waveguides to the photodetectors. This can avoid the trade-off between the responsivity and the transition-time-limited bandwidth by decoupling the optical path and electric path [9]. However, the serious absorption by p-InGaAs and metal contact layers prevents the pin photodetectors with an evanescent coupling scheme from practical applications as shown in the following section. This problem can be effectively solved by introducing a central opening on the p-InGaAs and metal contact layers, however. Furthermore, the absorption resonance phenomenon is observed and the thickness of the i-InGaAs layer is optimized towards efficient absorption.

II. Design and Discussion

Fig. 1 shows the cross section of an evanescently-coupled pin photodetector on an SOI waveguide. The i-InGaAs layer, serving as the intrinsic absorption layer, is sandwiched between an n-InP layer and a p-InGaAs layer. The n-type

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metal (not shown in the figure for clarity) is placed far away from the SOI waveguide on the n-InP lateral contact layer, and, therefore, has no influence on the optical coupling. However, p-type contact layers, i.e., the p-InGaAs and the metal contact are in direct touch with the optical field in the III-V layer (see Fig. 2). Thereby, a considerable part of the optical power is lost due to the absorption by these layers. In order to estimate this loss, we calculated the absorbed power as a function of detector length for both the real structure and a virtual structure where we only take into account the unwanted absorption of the p-InGaAs and the metal contact layers (assuming no absorption in i-InGaAs). During the calculation, the thickness of the III-V layer system is optimized to achieve phase matching [10] between the fundamental modes of the decoupled SOI waveguide and the detector waveguide. The results are shown in Fig. 3. One may argue that this method is not accurate since setting the imaginary part of the refractive index of i-InGaAs to zero may influence the field profile. However, according to our mode calculations, the relative difference between the real parts of the detector's modal effective indices of the above two situations is less than 0.05%, indicating that setting the imaginary part of the refractive index of i-InGaAs to zero imposes little effect on the field distribution. From Fig. 3, one sees that the absorption by the p-InGaAs and the metal contact layers is quite serious. Without the absorption of i-InGaAs, the light power can still be absorbed by 90% within just 20µm as a result of the unwanted absorption by the p-type contact layers. The light absorbed by these layers is lost, since it does not contribute to the generated photocurrent [11]. Therefore, it is necessary to reduce this loss for an efficient photodetector.

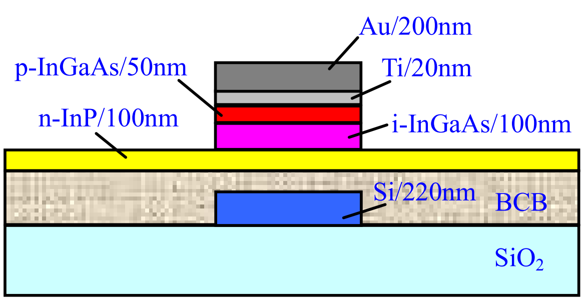

Fig. 1. The cross section of a pin photodetector evanescently coupled with an SOI waveguide. The thickness of each layer is also shown.

In order to reduce the power absorbed by the p-type contact layers, a straightforward way is to introduce an extra p-InP cladding layer between the i-InGaAs and p-InGaAs layers. However, the thickness of the p-InP cladding layer is very difficult to choose. On one hand, a thick p-InP layer is needed to effectively isolate the i-InGaAs and p-InGaAs layers. On the other hand, considerable part of the optical field will distribute in the p-InP cladding layer and consequently, isn't confined and absorbed by the i-InGaAs layer if a thick p-InP layer is used (due to the weak confinement in the vertical direction of the detector waveguide), which makes the absorption by the i-InGaAs layer less efficient. Furthermore, a thick p-InP layer increases the effective index of the detector waveguide mode, making it difficult to achieve phase matching between the SOI waveguide mode and the detector waveguide mode.

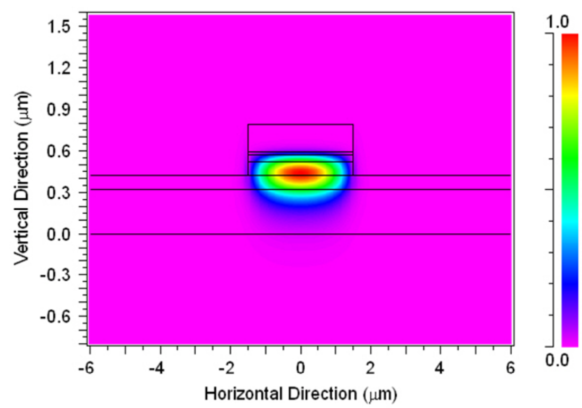

Fig. 2. The decoupled detector waveguide mode for a conventional design.

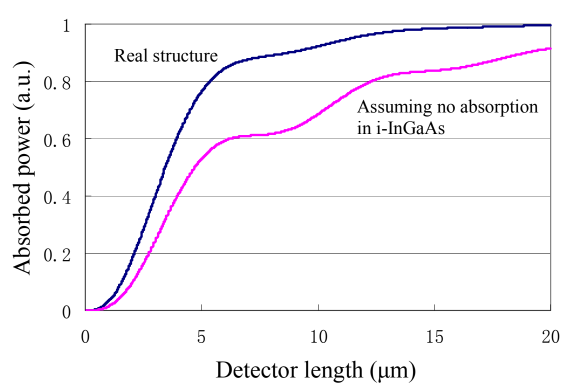

Fig. 3. The absorbed power for both the real structure and a virtual structure with no i-InGaAs absorption. The structure used is shown in Fig. 1.

This problem can be effectively solved by introducing a central opening on the p-contact layers as shown in Fig. 4. In order to maintain a uniform electric filed distribution in the i-InGaAs layer under a reverse bias, an extra p-InP conduction layer is embedded between the p-InGaAs and i-InGaAs layers.

Due to the large imaginary parts of the metal contacts on both sides of the detector mesa, the optical mode is confined in the central part of the mesa (see Fig. 5), and the overlap of the optical field with the p-type contact layers is reduced significantly. Again, we calculated the absorbed power for both the real structure and a virtual structure with no i-InGaAs absorption. The results are shown in Fig. 6. One sees that the absorption by the p-type contact layers is now reduced to less than 5% of input power, while the absorption of the real structure is over 98%. This indicates that the detrimental absorption of the contact layers is effectively suppressed without sacrificing the absorption efficiency of the i-InGaAs layer.

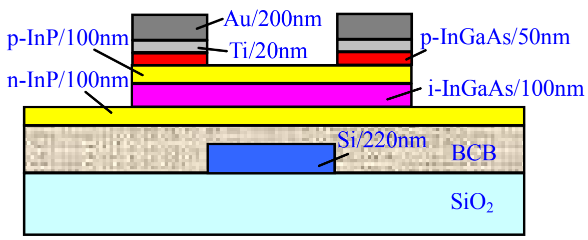

Fig. 4. The cross section of a novel configuration of a pin photodetector evanescently coupled with an SOI waveguide, where a central opening is introduced on the p-contact layers.

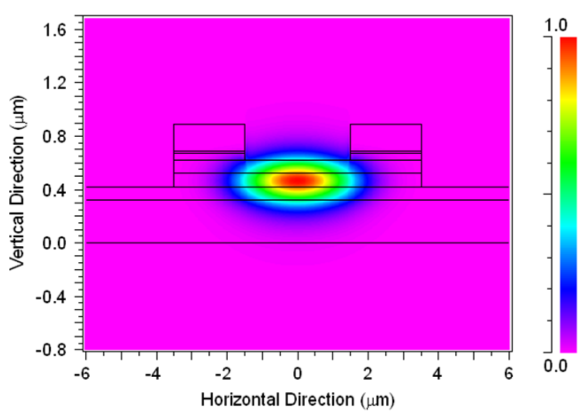

Fig. 5. The decoupled detector waveguide mode, where a central opening is introduced on the p-contact layers.

We also calculated the absorbed power as a function of the thickness of the i-InGaAs layer for a detector length of 20μm (see Figure. 7). Different BCB bonding-layer thicknesses are considered. The absorption resonance phenomenon is visible in the figure. The optimal thicknesses for the i-InGaAs layer to achieve efficient absorption are 100nm, 450nm and 800nm. Different absorption peaks occur when the fundamental mode of the SOI waveguide is phase-matched with different orders of detector waveguide modes. It is shown that an absorption efficiency over 95% is possible for a BCB bonding-layer thickness up to 150nm if the i-InGaAs layer thickness is carefully chosen. Considering the ease of fabrication (e.g., wet etching of the detector mesa), a thinner i-InGaAs layer is preferable.

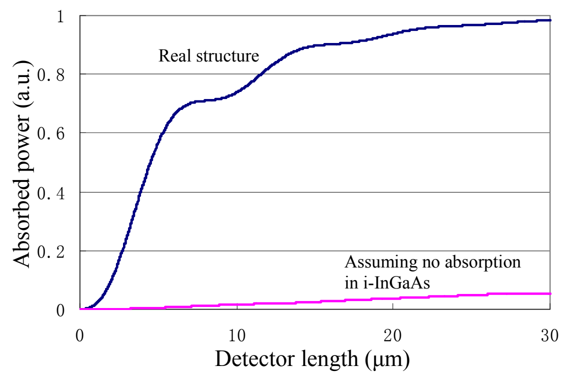

Fig. 6. The absorbed power for both the real structure and a virtual structure with no i-InGaAs absorption. The structure used is shown in Fig. 4.

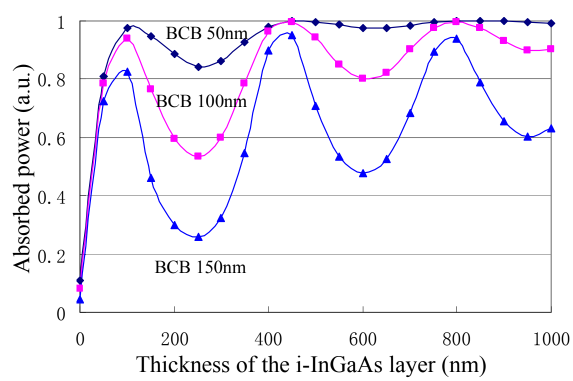

Fig. 7. The absorbed power as a function of the thickness of the i-InGaAs layer for a detector length of 20μm.

Based on the above discussions, the layer structure of the III-V pin photodetector can be determined and is shown in Table 1.

Table 1 Layer structure of the III-V pin photodetector.

Material	Doping type	Doping concentration (cm^{-1})	Thickness (nm)
$In_{0.53}Ga_{0.47}As$	p	1.0×10^{19}	50
InP	p	8.0×10^{18}	100
$In_{0.53}Ga_{0.47}As$	undoped	—	100
InP	n	2.0×10^{18}	100

III. Conclusion

Evanescent coupling between SOI waveguides and heterogeneously-integrated III-V pin photodetectors is investigated. The detrimental absorption by the p-InGaAs and metal contact layers is greatly reduced by introducing a central opening on these layers. While the absorption resonance phenomenon is observed, the thickness of the i-InGaAs layer is optimized towards efficient absorption. The fabrication of the proposed photodetectors is ongoing.

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