Horizontal p-i-n High-Speed Ge Waveguide Detector on Large Cross-section SOI Waveguide

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Abstract: We report a novel high-speed Ge photodetector on a large cross-section SOI waveguide platform. The device is butt-coupled with waveguide using a horizontal p-i-n junction configuration to enable high-speed operation. A very compact Ge detector with an active area of only 0.8 x 10 μm^2, greater than 32GHz optical bandwidth at -1V of reverse bias, and a responsivity of 1.1A/W is demonstrated.

OCIS codes: (040.5160) Photodetectors, (230.3120) Integrated optics devices, (250.5300) Photonic integrated circuits.

1. Introduction

The substantial growth in the past few years in web based multi-media and social networking applications is putting a significantly larger amount of data traffic on the current telecom and data infrastructure. High-speed interconnect technologies are needed to enable the projected growth in data handling. It is widely accepted that Si photonics, due to its electronics integration capability, proven manufacturing record and price-volume curve, will be the platform of choice for the next generation interconnect and communication solutions needed to address the projected bandwidth bottlenecks. This has fueled significant research and development work in this area in the past few years [1-10]. Many silicon-based active photonics components, such as high-speed modulators and Ge photodetectors [3-6] have been demonstrated on submicron waveguides. However, submicron SOI waveguides still suffer from high fiber coupling loss, high polarization dependent loss and large waveguide birefringence and phase noise. As a result they do not provide a satisfactory platform for implementation of passive and WDM devices. On the other hand, many high performance optical components have been demonstrated for large cross-section SOI waveguides (3 to 4 um core), such as commercially available VOAs, Echelle gratings and triplexer filters [7-10] exhibiting low fiber coupling loss, low waveguide propagation loss, low polarization dependent loss (PDL) and low polarization dependent frequency (PDF) shift. However, to our knowledge, a compact, high-speed photodetector has never been demonstrated using such large cross-section SOI waveguides. In this paper, we propose and demonstrate a novel, compact, high speed Ge photodetector efficiently butt-coupled with a large cross-section SOI waveguide in which a Ge p-i-n junction is placed in the horizontal direction. A very compact Ge detector with an active area of only 0.8 x 10 μm^2, and high speed performance with greater than 32GHz optical bandwidth at -1V of reverse bias is demonstrated. The device operates with a responsivity of 1.1A/W at a wavelength of 1550nm, a dark current of 0.26μA at a reverse bias of -0.5V. The demonstrated Ge photodetector enables integration with high performance, polarization independent de-multiplexers made using compatible large cross-section SOI waveguides, to form monolithically integrated silicon photonics receivers for multi-channel terabit data transmission applications.

2. Device design, structure and fabrication

A novel Ge photodetector is proposed and demonstrated here. The photodetector and the cross-section of the active p-i-n diode region are schematically shown in Figures 1(a) and 1(b) respectively. As the light propagates from the ridge SOI waveguide to the photodetector region, the light is butt-coupled and absorbed in the active Ge region where photocurrent is generated. This butt-coupled configuration allows a good overlap between the SOI waveguide mode and the Ge waveguide mode, and makes a very short active length possible. The Ge length only needs to be 10μm to absorb over 98% of the light as its absorption coefficient is around 4000cm^{-1}. This horizontal p-i-n configuration enables a very narrow intrinsic Ge region, hence reducing the transit time in this region. For a i-Ge width of 0.65um, a transit time limited speed >40GHz is calculated. The Ge sidewalls and slabs were doped to form the p and n regions. The SOI waveguide was 3μm wide to ensure low coupling loss with a lensed fiber or reduced core fiber. The Ge waveguide has a narrower width and is connected to the SOI waveguide by a horizontal taper.

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The photodetector was fabricated on six inch SOI wafers with a 3μm thick silicon epitaxial layer. First, the silicon recess region was formed by etching the silicon layer down to 0.6μm residual thickness above the BOX layer. Then, a 100nm thick Ge buffer layer was selectively grown at 400°C, followed by 4μm thick Ge growth at 670°C inside the silicon recess region. The Ge film was intentionally over grown, then thinned down and planarized with a chemical-mechanical polishing (CMP) step. The wafers then underwent a Ge anneal to reduce the threading dislocation density in the Ge film. The silicon ridge waveguides, Ge waveguides, and the silicon horizontal tapers were formed by the same etching step. As the etching rate of Ge is greater than that of silicon, additional etching in the silicon region was performed, forming a silicon ridge waveguide with a 0.6μm thick slab and a Ge ridge waveguide with a 0.2μm thick slab. Boron and phosphorus were implanted in the sidewalls and slabs of the Ge waveguide to form a horizontal p-i-n junction and p-type and n-type ohmic contact areas. After rapid thermal annealing (RTA) dopant activation, the Ti/Al metal stack was deposited and patterned to form p-type and n-type metal contacts. Finally, oxide and nitride films were deposited as waveguide cladding and passivation layers.

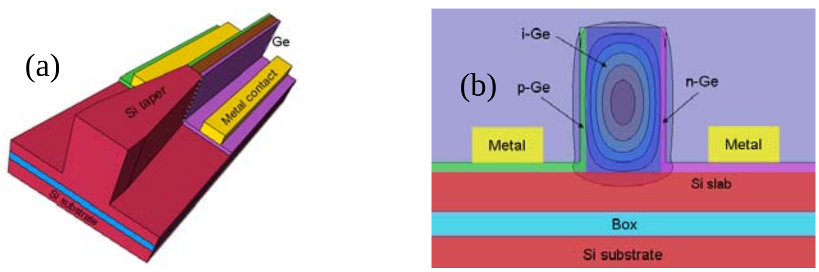

Fig. 1. (a) Schematic view of Ge photodetector integrated with SOI waveguide. (b) Cross-section view of the Ge p-i-n region.

3. Measurement results and discussion

A lensed fiber with a spot size of 3.3μm was used to couple light into the SOI waveguide. The optical power from the lensed fiber was 100μW. The photocurrent is calculated by subtracting the dark current from the total current under illumination. The dark current at -0.5V and -1V reverse biases was measured at 0.24μA and 1.3μA, respectively. In order to determine the responsivity of the photodetector, the fiber to waveguide coupling loss and the loss due to the SOI ridge waveguide were measured for the neighboring waveguides without the Ge detector. The measured fiber to waveguide coupling loss was 1.2dB, and loss from the SOI waveguide was 0.2dB, so the optical power that reached the Ge detector was about 72.4μW. The measured photocurrent for TE and TM polarized light were 77μA and 80μA respectively. The responsivity is calculated as 1.06A/W and 1.1A/W at 1550nm wavelength for TE and TM polarizations respectively. This corresponds to a quantum efficiency of 88%. The responsivity of the above device over the wavelength range from 1260nm to 1640nm was also measured at -1V reverse bias voltage, and is shown in Figure 2 (a). The ideal responsivity with 100% quantum efficiency is plotted on the same graph. This demonstrates satisfactory operation over a very wide wavelength range. The measured responsivity follows the quantum limit curve up to 1560nm. The device also shows very low polarization dependent responsivity. The roll-off in responsivity after 1560nm is due to the decreased absorption of Ge. The responsivity at longer wavelengths can be increased simply by increasing the length of Ge without sacrificing the speed of the device, as the device is not RC limited.

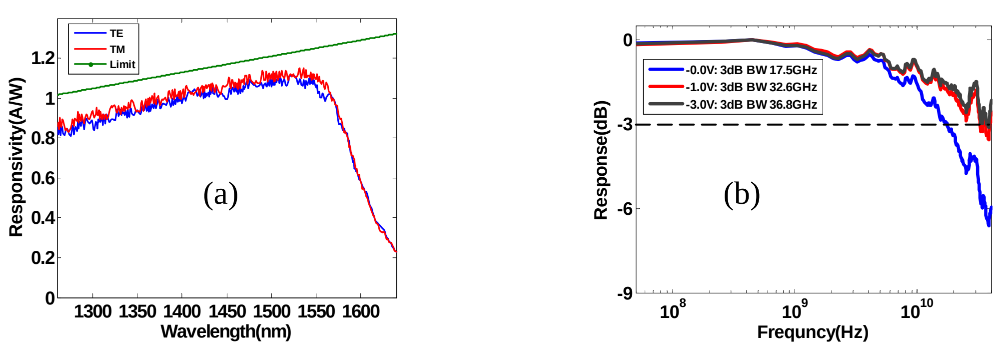

Fig. 2. (a). Measured responsivity of TE and TM polarization light. (b) Measured frequency response for the device.

The frequency response of the above described device was measured by a vector network component analyzer. A high-speed RF signal was applied to an external high-speed modulator with a bandwidth of about 40GHz. A reverse voltage bias was applied to the device through a bias-tee. The modulated light at 1550nm was then coupled to the device and the electrical output was measured through a high speed RF probe. The system, including RF cable, bias-tee, and modulator was calibrated and its response was factored out from the high-speed results. Fig. 2. (b). shows the normalized optical response for the detector with an active area of 0.8μm x 10μm and 0.65μm width of intrinsic Ge. The measured optical bandwidths are 17.5GHz, 32.6GHz and 36.8GHz at bias of 0V, -1V and -3V respectively. The device at -1V bias is fast enough to detect a 40Gbs/s optical signal.

4. Conclusion

In conclusion, we have demonstrated a high-speed Ge photodetector integrated with a large cross-section SOI waveguide. A novel butt-coupled Ge horizontal p-i-n junction was used to enable very high-speed operation. The demonstrated device has a very compact active area of only 8μm^2, a 3dB bandwidth of over 32GHz at -1V reverse bias, and a responsivity as high as 1.1A/W at 1550nm wavelength. To the best of our knowledge, this is the first demonstration of a high-speed, high responsivity, compact Ge photodetector integrated with large cross-section SOI waveguides. The process used to fabricate such a device is fully compatible with CMOS technology developed for microelectronic circuits. The device can readily be integrated with high performance WDM filters on large cross-section SOI waveguides to build an integrated silicon photonics receiver for the next generation optical interconnect and telecommunication applications.

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