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Mode-Evolution Based Coupler for Ge-on-Si Photodetectors

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Abstract: We demonstrate a mode-evolution based coupler for Ge-on-Si photodetectors achieving uniform power absorption in germanium leading to an 88% increase in photocurrent generation under 29mW illumination. We also measure a 7.4mA/cm^2 dark current density at -1V, 1550nm responsivity of 1.01A/W and 40GHz 3-dB electro-optic bandwidth.

1. Introduction

The successful development of a CMOS-compatible germanium-on-silicon (Ge-on-Si) fabrication process [1-3] has promoted germanium as a viable option for near-infrared (NIR) light detection in guided-wave integrated photonic systems. One remaining challenge with using germanium photodetectors at NIR wavelengths is the large impedance mismatch between silicon bus waveguides and Ge-on-Si structures. To this day, only mode coupling schemes have been investigated [4-7]. This type of coupling is inherently not broadband and leads to a nonuniform generation of electron-hole pairs in germanium. In this paper, we demonstrate a Ge-on-Si photodetector with an efficient and compact mode-evolution based coupler to transfer light from the silicon bus waveguide to the detector. Compared to butt coupled devices, these detectors generate 88% more photocurrent at an input power of 29 mW due to a uniform distribution electron-hole pair generation in germanium.

2. Photodetector Design and Simulation

An illustration of a vertical p-i-n Ge-on-Si photodetector with the mode-evolution based coupler is shown in Fig. 1(a) and with a butt coupler in Fig. 1(b). In Fig. 1(a), a silicon bus waveguide is brought to a distance of 100nm from the Ge-on-Si photodetector using a 5µm radius bend converting the isolated bus waveguide mode to the symmetric mode of the full structure (Fig. 1(c)). Then, the 400nm wide bus waveguide is tapered on one side down to a width of 100nm over the length of the detector to remain in the symmetric mode (Fig. 1(c)). The symmetric mode evolves from the TE_{11} mode in the bus waveguide to the TE_{13} mode in the Ge-on-Si photodector. In practice, wider detectors are desired for maximal confinement in germanium at the expense of supporting a larger number of modes. However, as long as coupling to unwanted mode pairs is minimized, the mode-evolution theory holds. This can be seen from the equation for power lost to an unwanted mode m, which is given in [8]: $P_m \propto 2|\bar{\kappa}/\overline{\Delta\beta}|^2[1-\cos(\overline{\Delta\beta}y)]$. Here $\overline{\Delta\beta}$ represents the average propagation constant difference between mode pairs and is constant regardless of the taper length. $\bar{\kappa}$ is the average coupling coefficient, which can be minimized with a long taper. These conditions will guarantee that the unwanted power transfer, P_m, will approach zero because $|\bar{\kappa}/\overline{\Delta\beta}| \ll 1$.

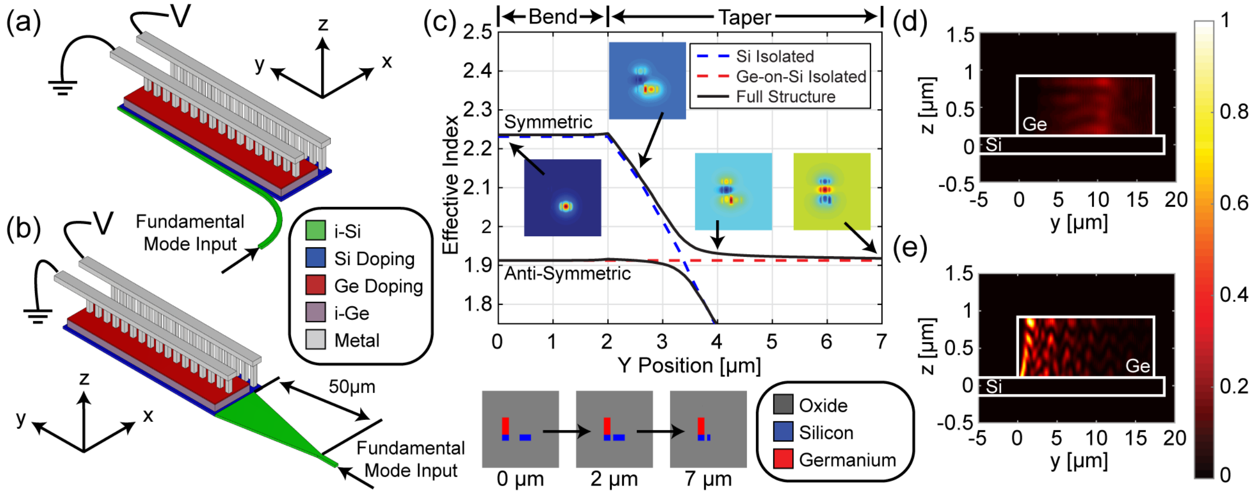

Fig. 1. 3D illustration of the Ge-on-Si photodector with (a) mode-evolution based coupler and (b) butt coupled input. In (a), the image is to scale, but in (b) the linear 50µm taper is not to scale. (c) Evolution of the mode from TE_{11} in the silicon (Si) waveguide to TE_{13} in the Ge-on-Si photodetector with a cross-section of the device structure given below. For this simulation, the germanium was assumed to be single-mode in the x-direction to reduce the number of supported modes. Simulated normalized power absorption in the intrinsic germanium region for the (d) mode-evolution based coupler and (e) butt coupled input.

The mode-evolution based coupling is advantageous because it will lead to a uniform absorption of power in the intrinsic region of the germanium layer. Fig. 1(d,e) show the absorbed power as a function of position in a 1.5µm wide by 16.75µm long photodetector. Light from a butt coupled input excites multiple modes in the Ge-on-Si structure, which leads to concentrated locations with high power absorption (Fig. 1(e)). The mode-evolution based coupler produces a uniform power absorption, Fig. 1(d), leading to a higher saturation power compared to the butt coupler.

3. Photodetector Measurements

The photodetectors were fabricated in a state-of-the-art CMOS foundry on a 300mm SOI wafer with 220nm silicon height and 2µm buried oxide using 193nm immersion lithography [3]. Fig 2(a) shows the dark current of 1.5×11.75µm and 4×6.75µm Ge-on-Si detectors. A 2nA dark current is measured at -1V bias (7.4mA/cm^2 dark current density) in the 4×6.75µm device. The responsivity of the germanium photodetectors was measured at -1V bias using both the mode-evolution based coupler and butt coupler as a function of wavelength (Fig. 2(b)). The wider photodetectors exhibit a higher responsivity due to more absorption in the intrinsic germanium region [6]. For the 4×6.75µm device, a responsivity of 1.01A/W is observed at 1550nm using the mode-evolution based coupler. The 3-dB electro-optic bandwidth for both sizes of detectors was measured to be 40GHz, which is limited by the free carrier transient time.

To compare saturation powers, the narrower 1.5µm width was chosen over the wider 4µm width photodetector to increase the peak intensity inside of the device given that both are illuminated with the same incident power. Each coupling scheme was examined at two different germanium lengths of 11.75µm and 16.75µm. The generated photocurrent was measured as a function of input power (Fig. 2(c)). Both coupling schemes exhibit a nearly constant responsivity over a range of input powers spanning ~10nW to 10mW. Past an input power of 10mW, a saturation in photocurrent generation is observed in both of the butt coupled photodetectors limiting the maximum output current to 9.3mA. In contrast, given a source limited input power of 29mW, the detectors with the mode-evolution based coupler produce a photocurrent of 15.75mA and 17.5mA in the 11.75µm and 16.75µm long devices respectively. These results correspond to a 69% and 88% improvement in output current at this input power level.

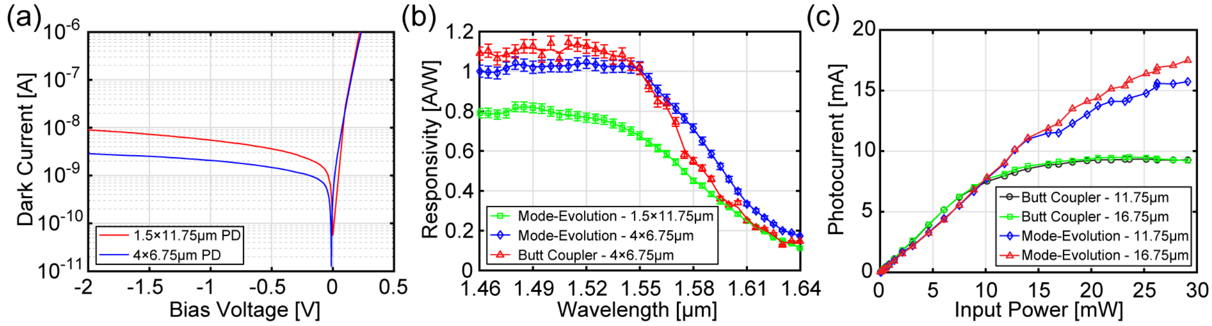

Fig. 2. (a) Measured dark current of Ge-on-Si photodetectors (PD) as a function of bias voltage. (b) Measured responsivity of 1.5×11.75µm mode-evolution coupled and 4×6.75µm mode-evolution and butt coupled photodetectors as a function of wavelength. The error bars correspond to a ±3% uncertainty in the coupling. (c) Measured photocurrent as a function of input power for 1.5µm wide photodiodes with butt coupled and mode-evolution based inputs with lengths of 11.75µm and 16.75µm.

4. Conclusions

We demonstrated a new compact coupling scheme to efficiently transfer TE-polarized light from a silicon bus waveguide into a Ge-on-Si photodetector. Our results show that the mode-evolution based coupler provides a high responsivity of 1.01A/W at 1550nm, and that this level of responsivity is maintained over a range of input powers spanning 6 orders of magnitude. For input powers exceeding 10mW, this new coupling method provides up to 88% more photocurrent generation compared to butt coupled photodiodes.

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References

1. H. C. Luan, *et al.*, "High-quality Ge epilayers on Si with low threading-dislocation densities," Appl. Phys. Lett. **75**, 2909 (1999).
2. J. Michel, *et al.*, "High-performance Ge-on-Si photodetectors," Nat. Photon. **4**, 527 (2010).
3. E. Timurdogan, *et al.*, "An Ultra Low Power 3D Integrated Intra-Chip Silicon Electronic-Photonic Link," in Optical Fiber Communication Confernce Postdeadline Papers, OSA Technical Digest (online) (Optical Society of America, 2015), paper Th5B.8.
4. T. Yin, *et al.*, "31GHz Ge n-i-p waveguide photodetectors on Silicon-on-Insulator substrate," Opt. Express **15**, 13965 (2007).
5. D. Feng, *et al.*, "High-speed Ge photodetector monolithically integrated with large cross-section silicon-on-insulator waveguide," Appl. Phys. Lett. **95**, 261105 (2009).
6. C. T. DeRose, *et al.*, "Ultra compact 45 GHz CMOS compatible Germanium waveguide photodiode with low dark current," Opt. Express **19**, 24897 (2011).
7. C.M. Chang *et al.*, "High-power dual-fed traveling wave photodetector circuit in silicon photonics," Opt. Express **23**, 22857 (2015).
8. M. R. Watts *et al.*, "Integrated Mode-Evolution-Based Polarization Splitter," Opt. Lett. **30**, 967 (2005).