Resonant Germanium-on-Silicon Photodetector with Evanescent Waveguide Coupling

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Abstract: A 4.5-µm-radius resonant germanium-on-silicon photodetector is first demonstrated with evanescent coupling from bus waveguide, achieving 2.03nA dark current, 1.04A/W responsivity at 1530nm, 32.9GHz electro-optic bandwidth and enhancement on responsivities for longer wavelengths (>0.3A/W at 1630nm).

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (040.5160) Photodetectors.

1. Introduction

Silicon photonics provides a promising solution to address the ever-demanding bandwidth and power-consumption bottlenecks in both on- and off-chip interconnections. The active involvement of well-established Complementary-Metal-Oxide-Semiconductor (CMOS) foundries paves the way for custom fabrication processes tailored for large-scale electronics-photonics integrations [1,2]. Thus far, near infrared photodetection has been realized in a variety of materials, including germanium, polycrystalline silicon, III-V materials, and two-dimensional materials. Among them, germanium has the advantages of high responsivity and CMOS-compatible integration on silicon. While germanium detectors using butt- or evanescent-coupled waveguide designs in guided optics have been demonstrated before [3], the interaction length is still relatively short to enable efficient detection of longer wavelength (e.g. L band – 1565 to 1625nm). This, however, can be compensated by utilizing resonant-based structures. While resonant detectors have been demonstrated in polycrystalline silicon [4,5], resonant germanium photodetectors integrated on silicon photonic platform are to-date unexplored.

Here, we designed and demonstrated the first resonant germanium-on-silicon photodetector with evanescent coupling from the bus waveguide. The device has a radius of 4.5µm with dark current as low as 2.03nA and peak responsivity of 1.04A/W at λ~1530nm when the detector is biased with -1V. The compact size reduces the overall device capacitance, resulting in a detection bandwidth of 32.9GHz. The resonant nature further extends the detection wavelength range to 1630nm with >0.30A/W responsivity, enabling four times enhancement on responsivity compared to detector demonstrated in Ref. [1], which was fabricated using the same germanium recipe. In addition, due to its wavelength selective nature, both wavelength filtering and power detection functions are achieved in the same device, which can potentially simplify the architecture for wavelength-division-multiplexing (WDM) and multicasting networks [6].

2. Designs and Experimental Results

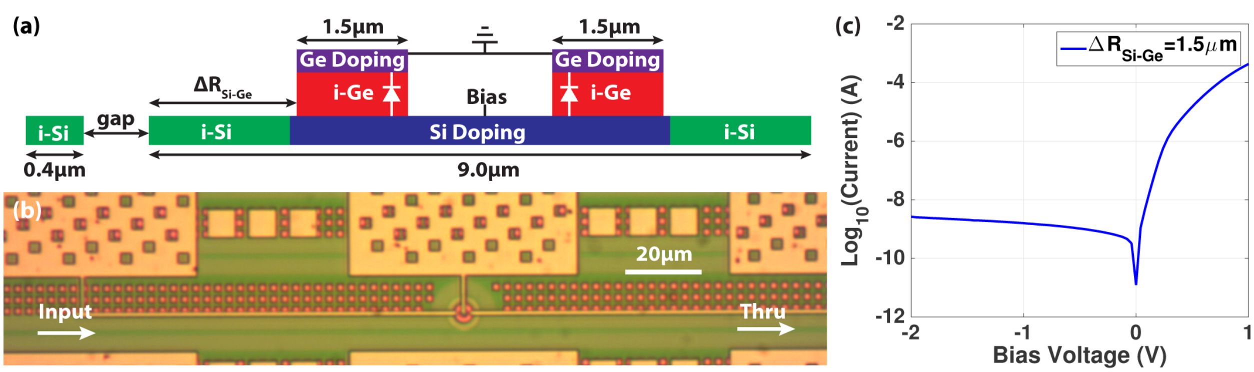

Fig. 1 – (a) Schematic cross-sectional view of the resonant germanium-on-silicon detector. $\Delta R_{Si\text{-}Ge}$ stands for the difference between germanium and silicon outer-radius. (b) Top-view optical microscope image of the fabricated resonant detector. (c) I-V curves of resonant detector with $\Delta R_{Si\text{-}Ge}$ = 1.5µm, showing nA-scale dark current at -1V bias voltage.

A schematic cross-sectional view of the resonant-based germanium-on-silicon detector is shown in Fig. 1(a). The waveguide width is 400nm to ensure single-mode in the bus waveguide. $\Delta R_{Si\text{-}Ge}$ in Fig. 1(a) stands for the difference between germanium and silicon outer-radius. Silicon doping (bottom of Fig. 1(a)), intrinsic germanium (i-Ge) and germanium doping together form the p-i-n junction of the resonant detector. For metal contact to the germanium, circular contact [7] is utilized to bring the contact close to where the carriers are generated, which further reduces the device resistance. Input power from bus waveguide is coupled into the resonator and absorbed inside the cavity. The lossy regions within the cavity are silicon doping, germanium and metal contacts. The overlap between the resonant mode and lossy regions should be reduced to improve photodetector responsivity. Thus, the distance between germanium and silicon outer-radius ($\Delta R_{Si\text{-}Ge}$) is carefully selected to be 1.5μm to allow a small tail of the resonant mode to be in the i-Ge, reducing overlap with lossy regions. Through matching the external quality factor (Q-factor) to the intrinsic Q-factor of the cavity, power at the resonant wavelength can be fully absorbed with high quantum efficiency. Besides, micro-resonator design and evanescent coupling minimize the back-reflection, which is one of the limiting factors on responsivity for butt-coupled photodetectors. The device was fabricated in a state-of-art CMOS foundry, using same process utilized in Ref. [1]. The top-view optical microscope image of the fabricated device is shown in Fig. 1(b). The dark current of the device with $\Delta R_{Si\text{-}Ge}$ = 1.5μm is shown in Fig. 1(c), showing 2.06nA dark current under -1V bias voltage.

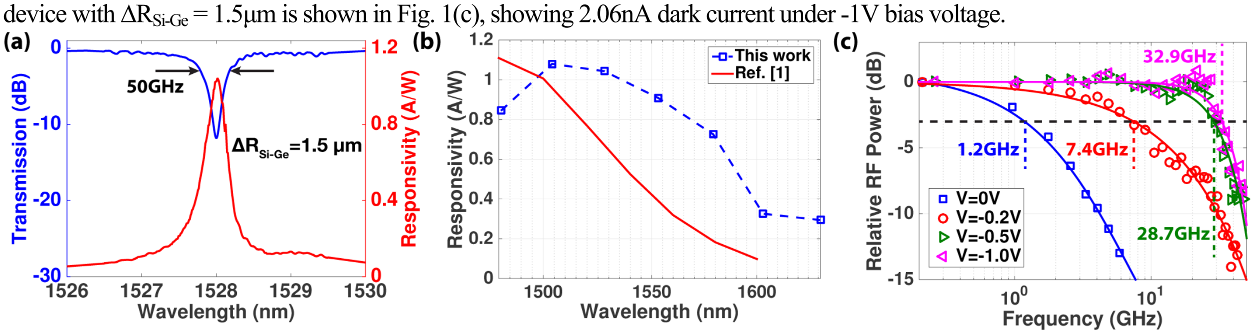

Fig. 2 – (a) Transmission spectrum and responsivity of resonant detectors at 100nm bus-to-resonator gap for wavelength around 1528nm, showing 50GHz full-width-half-maximum bandwidth. (b) Responsivities of the resonant detector for different wavelength with 100nm coupling gap. Evanescent-coupled waveguide detector responsivity curve (red solid line) from Ref. [1] is included here for comparison. (c) Measured bandwidths of the devices with different bias voltages for device with 100nm gap, showing 3dB bandwidth of 32.9 GHz for -1V bias.

The transmission spectrum and responsivity of the resonant detector are shown in Fig. 2(a). A peak responsivity of 1.04A/W is achieved around 1528nm. The full-width-half-maximum (FWHM) bandwidth of resonator is 50GHz. With the resonant nature of the device, responsivity for longer wavelength is enhanced due to interaction length increase. The responsivities for different wavelengths are shown in Fig. 2(b). Compared to waveguide detector fabricated under the same process in Ref. [1], the resonant device provides a four times enhancement to the detector responsivity for longer wavelength. The electro-optic bandwidth of the detector was measured using the heterodyne laser technique. Fig. 2(c) shows the measured bandwidth of the device with 100nm coupling gap size for wavelength around 1528nm under different bias voltage. Bandwidth of detector is improved from 1.2GHz under zero bias to 32.9GHz under -1V or more reverse bias, indicating a velocity saturation. The electrical-optic bandwidth measured is less than optical bandwidth (50GHz), which is mainly limited by the transit time of the germanium material. The wavelength-selective nature and high-speed performance make it a suitable building block in WDM and multicasting networks.

3. Conclusion

To summarize, we designed and demonstrated a compact (4.5-μm-radius), low dark current (2.03nA), high-responsivity (1.04A/W) and high-bandwidth (32.9GHz) resonant germanium-on-silicon photodetector on integrated silicon photonics platform. With the resonant nature of the device, the detection wavelength range is further extended to 1630nm with >0.30A/W responsivity, making it possible to handle S, C and L band power detection using the same device. Besides, resonant detectors are suited for simplifying architectures of WDM and multicasting networks. A WDM system where each channel is filtered and received and a multicast network where a wavelength channel is routed to multiple end points can be readily achieved using cascaded resonant germanium-on-silicon detectors.

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4. References

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