Germanium-on-Silicon photo-detectors based on tiny micro-disk resonators

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Abstract: Micron-scale disk resonators are explored to minituarize and enhance Ge-on-Si photodetectors. A 2.0 μm-radius detector exhibits a dark current of 11 nA, a responsitivity of 0.5 A/W and a 3-dB bandwidth of 17 GHz at -1V bias.

1. Introduction

Microdisk is a striking planar structure in integrated optics to enhance light-matter interaction and construct various photonics devices. The disk geometries feature in strongly and circularly confining light into an ultra-small volume in the form of whispering gallery modes. A laser may benefit from a microdisk in which the mode of interest overlaps the gain materials both spatially and spectrally [1]. Compared to a micro-ring, a micro-disk removes the inner boundary to enable even better compactness, which also makes it very suitable for scenarios that electrical connections are needed. For example, an ultra-low power ($\approx fJ$) athermal Si modulator has been demonstrated with a bit rate of 25 $Gbit/s$ by confining both photons and electrically-driven carriers into a microscale volume [2].

A unique feature of using microdisk for Germanium photodetector (Ge PD) is that the mode selection is not important. In the applications of laser or other passive optical components, microdisk must be designed very carefully to excite the specific mode in a microdisk in that essentially the microdisk usually supports many higher-order modes in the radial directions [3]. However, for detector applications, this is not an issue because the local light absorption is mode insensitive. Light power carried by all modes are expected to be converted into photo-current. Another benefit of using microdisk is that the power recycling relies on light circulation inside the disk rather than introducing any high-performance reflectors that Fabry Perot cavity calls for.

In this work we study Si-based PDs with Ge selectively grown on a microdisk with radius of a few microns. Several Ge PDs built on Si micro-disks had been fabricated on the standard Si photonics multiple project wafers (MPW) and demonstrated to exhibit very low dark current, satisfactory operation bandwidth and moderate responsivity. Among them, a vertical p-i-n Ge PD based on a 2.0 μm-radius micro-disk has a dark current of as low as 11 nA, compared to a conventional PD current of $>$ 500 nA with an area of 200 μm^2 [4]. The operation bandwidth is around 17 GHz at a reverse bias of -1 V. The responsitivity is about 0.5 A/W. A complete simulation model with all involved materials taken into account is established to study the promise of microdisk structures for PD usage by using finite difference time domain (FDTD) method. By viewing from the current preliminary data, the directions to further improve the device performance are also discussed.

2. Design and simulation

The studied Ge PDs are based on micro-disk resonators seamlessly coupled with an individual straight waveguide tangential to it. For electrical connection, a Si slab by shallow etching may be preferable, but it has worse light confinement. In this work, we fully etched the 220nm Si layer but connected the optical Si disk to another satellite disk for electrical connection through a short waveguide, as shown in Fig. 1(a). The waveguide is oriented to the opposite direction of light circulation in the microdisk to avoid unwanted power leakage. From optics point of view, the Ge-on-Si microdisk can be even smaller than its pure-Si counterpart due to the high dielectric constant of Ge. However, in the need of electrical connection over the Ge (100) facet, the resonator size is limited by the size of the contact hole, which is around 1μm considering the current lithography capability on the Ge topography. It should be noted that this is not an avoidable issue if one chooses isotropic Ge growth and chemical mechanical planarization (CMP) process to get rid of the long-tailed Ge (311) slope. Figure 1(b) shows an SEM image before the wafer enters into the back-end processes. An Ge island is successfully formed on the Si disk by selective epitaxial growth. It should be noted that the practical (311) surface is not that smooth as we illustrated in Fig. 1(a), which should be the major cause of scattering loss. By using finite difference time domain (FDTD) method, Figure 1(c) captures a snapshot of electric field in the microdisk after nearly $1ps$ excitation from the access waveguide. Light circulation within the PD is known to be at a steady state from monitoring the power in Ge. It can be concluded that high-order modes are excited within the microdisk due to light diffraction at the joint of the input waveguide and the disk because the fundamental gallery mode in a microdisk should be resonating closely and regularly along the disk edge. However, this is not an issue for PDs as long as light absorption and carrier-to-current conversion is complete. Assume that the responsivity of a Ge PD is proportional to the light absorption in Ge. In Fig. 1(d), we investigated the influence of the disk diameter to the light absorption in Ge. The Ge absorption factor (by setting the material extinction coefficient) is assumed to be 5 times larger than that of intrinsic Ge because of the lattice mismatching stress in epitaxial Ge on Si. We also considered the absorption of the doped Si mesa and the top metal (i.e. TaN here). Although larger disk is expected to absorb light more completely, but Fig. 1(d) shows that this is not true if considering 500A TaN materials properties in the device modeling as what we did in experiment. Light absorption drops down when the disk diameter goes up to $3\mu m$.

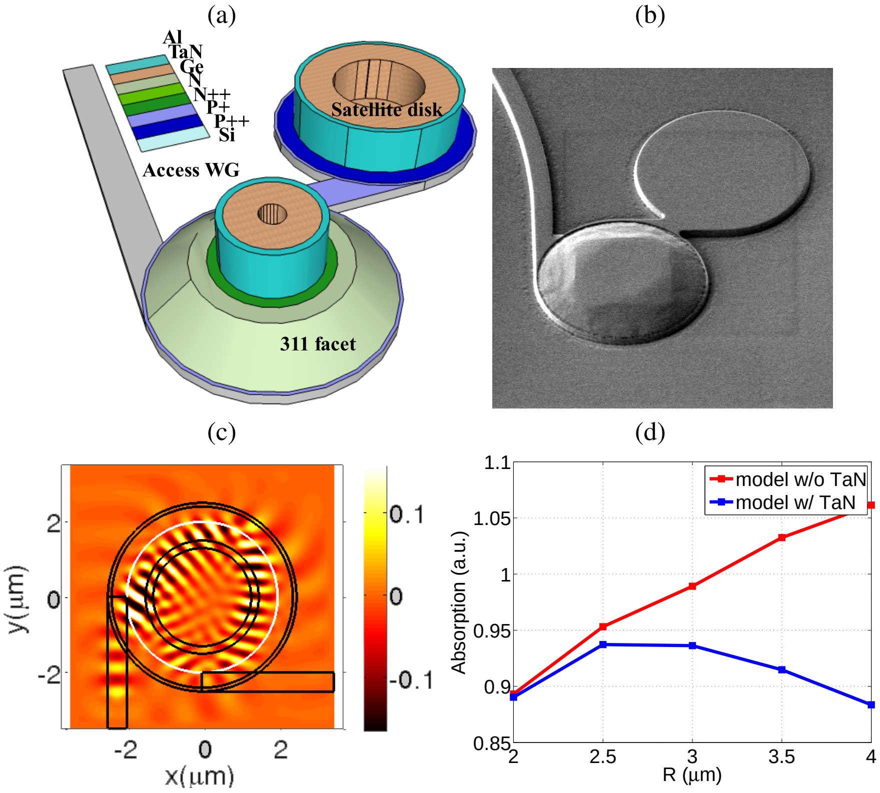

Fig. 1. (a) The bird view of a microdisk-based photodetector; (b) the SEM image of Ge formation on the mesa of Si disk; (c) A snapshot of light field circulation in the microdisk; and (d) a comparison of light absorption in Ge against the disk diameter.

3. Characterization

The PDs were fabricated by using the full integration processes that we standardized for IME MPW projects. The main aspects to verify the PD performance are the bandwidth, dark current and responsivity. All these parameters can be extracted by a simple setup that sequentially connects the lightwave component analyzer (LCA) optical output, polarization controller, input fiber, optical device, output fiber and power meter. The I-V characteristics are extracted from another 2-port electrical loop that connects the LCA microwave output port, the GS probe to DUT, the bias Tee, and the LCA microwave input port. The I-V characteristic curves in Fig. 2(a) shows that the dark current monotonically increase from -11 nA to 150 nA at a reverse bias of -1 V when the disk diameter increases from 2 μm to 4 μm. Then the input fiber is automatically aligned to device to obtain the photo-current shown in Fig. 2(b). The local power before entering the PD is calculated to be -11.3dBm by the monitored power that another branch of a 3dB power splitter in front of the PD access waveguide. The results show that the PD responsivity is around 0.5 A/W for a 2 μm-radius PD and 0.65 A/W for the 3 μm-radius case. This moderate value still has much room to improve by prohibiting the loss mechanisms in the PD absorption areas. It should be noted that there is some correlation between the Fig. 2(b) and Fig. 1(d) in the disk diameter dependence of light absorption. We expect that reducing the contact area over Ge (100) facet will be beneficial to the PD responsivities of larger PDs. The 3-dB bandwidth increases with the reversely biased voltage. It changes from 8 GHz to 21 GHz by raising the voltage from 0V to -8 V. This result shown in Fig. 2(a) indicates that this device could work well for 25 Gbps data transmission, which is under further verification of eye diagram by equipping the device with trans-impedance-amplifier (TIA). By comparing the PD data from our early MPW runs, we recognized that the series resistance is relatively high in this work by looking at the forwarded biased part of the I-V curves. The forward current at 1-V bias is just a fraction of mA, which is less than the 3mA of our standard PDs. We expect that the operation bandwidth can be further enhanced by improving the contact resistance and shortening the electrical path to the satellite disk.

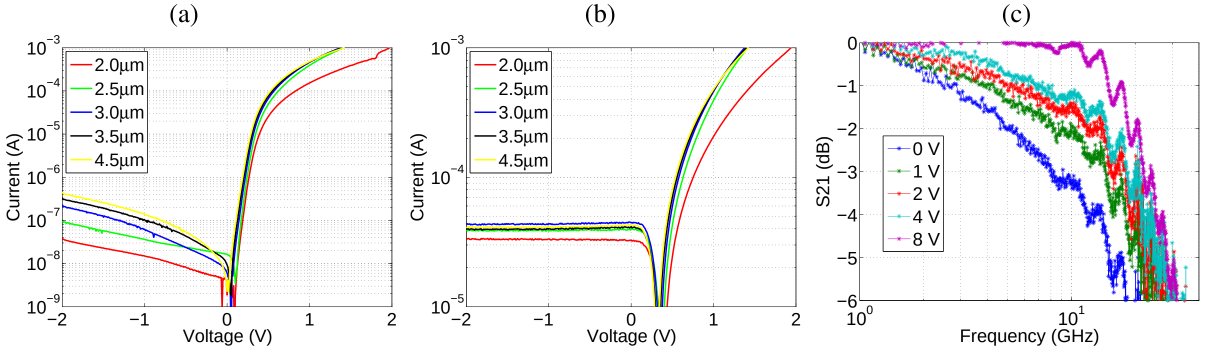

Fig. 2. The I-V characteristics of the PDs with various diameters without (a) and with (b) light illumination; (c) the bandwidth measurement of a photodetector with a radius of 2μm.

4. Summary

This work demonstrated that the micron-scale disks are promising for photodetector designs because of its capability of harvesting light energy in an ultra-small volume. The MPW standard process enables that all the major specifications are comparable to a standard PD designs. We expect that even smaller disks that may be realized by non-selective Ge epitaxy will further enhance the dark current performance and operation bandwidth.

Acknowledgments

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