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Microdisk enhanced photodetector based on Ge self-assembled quantum dots on silicon-on-insulator

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ABSTRACT

By embedding Ge self-assembled quantum dots (QDs) in microdisk cavity, resonant-cavity-enhanced waveguide photodetector (PD) with ultra-low dark current and high responsivity is experimentally demonstrated around 1.55 μm wavelength. Ge QDs are grown on silicon-on-insulator substrate by solid-source molecular beam epitaxy. Microdisk is used to enhance the absorption efficiency of Ge QDs, and a vertical PIN diode is integrated with the microdisk to extract photo-generated current. The dark current density of our PD is as low as 0.97 mA/cm^2 under −10 V bias. At resonant wavelength of 1541.15 nm, enhanced peak responsivity of 2.13 mA/W is obtained. The wavelength selectivity of the microdisk PD also makes it preferable for wavelength-division multiplexing optical receiver.

1. Introduction

Silicon (Si) photonics is thought to be one of the most promising solutions for power consumption and transmission speed issues in the global interconnection made by metal/dielectric system in microelectronic integrated circuits [1,2]. So far, Si has been demonstrated to be an excellent platform for passive photonic devices in the telecommunication band, such as waveguides, filters, modulators, and so on [3]. However, it is very challenging to make active devices such as light sources and photodetectors (PDs) directly from Si due to its indirect and large band gap. On the other hand, germanium (Ge), which has been widely used for high mobility electronic devices [4], is also one of the most important supplementary materials for photonics area, especially for PDs due to its large absorption coefficient in the telecommunication band [5]. PDs with high responsivity have been demonstrated by using pure relaxed Ge grown on Si [6–9]. However, the dark current of these PDs is usually relatively large due to the limited material quality of Ge on Si.

In the meanwhile, Ge self-assembled quantum dots (QDs) can be easily grown on Si free of dislocation [10–12]. But their thickness is usually very small, limited by the critical thickness due to the lattice constant mismatch between Si and Ge. By growing multi-layers of Ge QDs on Si, different types of PDs have been demonstrated [11,13–15]. However, the responsivity at near-infrared is very low due to the low absorption coefficient. By combining optical resonant cavities with Ge QDs, resonant-cavity-enhanced (RCE) PDs with enhanced responsivity can be realized [16,17]. At resonant wavelengths, light can be absorbed several times in the cavities, and absorption efficiency can be significantly enhanced. Moreover, due to this resonant property, RCE PDs are wavelength-selective, making them more preferable for wavelength-division multiplexing (WDM) optical receivers. Ge QDs based RCE PD with normal incidence configuration has been demonstrated with top and bottom mirrors made by Si/SiO_2 dielectric stacking [18]. However, the fabrication process is rather complicated and the responsivity is still very low due to the small absorption length limited by epitaxy growth. By using a waveguide configuration, the absorption length can be easily controlled [19]. Si-based microring and microdisk RCE PDs based on surface-state absorption [20], two-photon absorption [21], and sub-bandgap absorption [22,23] have been realized. In order to obtain high responsivity, however, the resonator size is rather large, typically from several tens to hundreds micrometers. In this paper, we demonstrated ultra-compact microdisk enhanced PDs based on Ge QDs on silicon-on-insulator (SOI) with only a few micrometers radius. The devices show good performance with ultra-low dark current and high peak responsivity around 1.55 μm.

2. Device structure and fabrication

We started material growth from SOI wafers with 160-nm-thick top Si layer (p type, resistivity of about 10 Ω·cm, corresponding to doping concentration of about 1.3×10^{15} cm^{-3}) and 2-μm-thick buried oxide layer. All of the Si/Ge layers were grown by solid-source molecular beam epitaxy (MBE) at nominal temperature of 700 °C. After a 40-nm-thick Si buffer layer, three layers of Ge QDs, separated by 20-nm-thick Si spacers were grown under Stranski–Krastanov mode. At last, the samples were capped by 200-nm-thick Si layer. The total Si/Ge layer thickness is about 470 nm, according to the cross-section scanning electron microscope (SEM) measurement (Hitachi S-4100, with an operating voltage of 15 kV). Fig. 1(a) shows the atomic force microscopy

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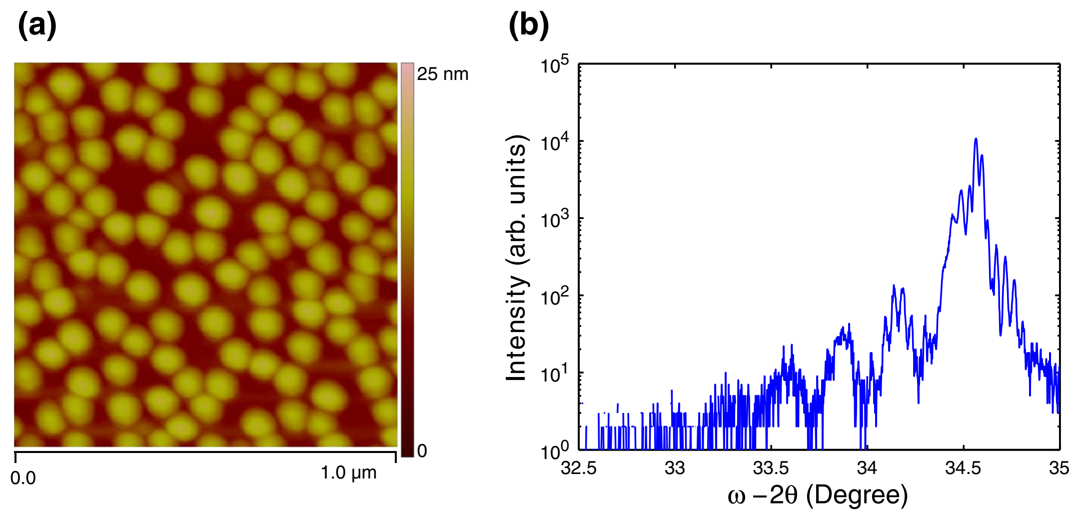

Fig. 1. (a) AFM image of the first layer of Ge QDs grown on SOI. (b) XRD rocking curve of the sample with three layers of Ge QDs grown on SOI.

(AFM) image of Ge QDs grown with the same condition but with only one Ge QDs layer and without Si cap layer, measured by Digital Instruments Nanoscope III AFM with a N + silicon single crystal probe under tapping mode. The overall dot density is around 9.5×10^9 cm^{-2}. The typical base diameter of the dots is around 80–95 nm, and the height is around 9.0–9.7 nm. The grown three layers of Ge QDs sample were also characterized by X-ray diffraction (XRD, Philips X'Pert MRD, with Cu-Kα line as the X-ray source, two asymmetrical Ge(220) single crystals before and after the sample as the monochromator and analyzer). The XRD rocking curve is shown in Fig. 1(b). Although the sample is with only three layers of Ge QDs and each layer is very thin, we can still observe several Ge-related satellite peaks, indicating good crystal quality. Room-temperature photoluminescence (PL) spectrum of the grown sample is shown in Fig. 2. The PL spectrum was measured by a confocal microscopy PL system, in which a 532 nm laser was focused onto the sample as excitation by an objective lens (100×, numerical aperture = 0.95), and the light emission was collected by the same lens, then dispersed by a monochromator and detected by a liquid-nitrogen-cooled InGaAs detector array. Strong Ge QDs related peak can be clearly seen around 1.5 μm. This peak energy is much smaller than the indirect band gap of Ge provided that the quantum confinement effect is small due to the large Ge QD size. This is due to the significant Si–Ge inter-diffusion at our growth temperature. The relative broad spectrum, especially above peak wavelength, however, indicates that there are still some Ge QDs with higher Ge composition. These QDs have smaller band gap, thus larger absorption coefficient around 1.5 μm wavelength range, and will dominate the photo-response.

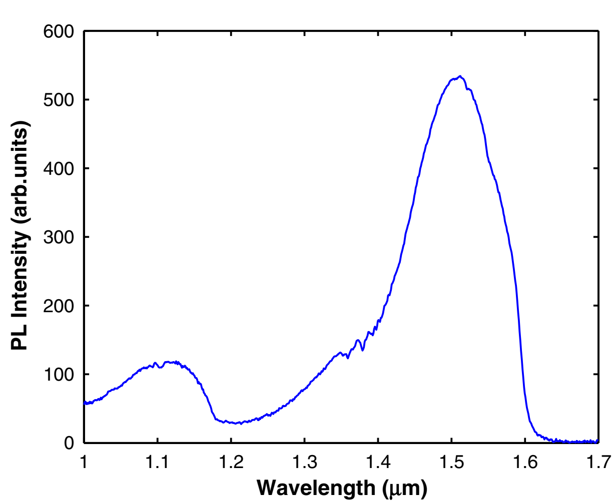

Fig. 2. Room-temperature PL spectrum of the sample with three layers of Ge QDs grown on SOI.

In order to enhance the absorption efficiency of Ge QDs, microdisks were exploited. The cross-section view of the microdisk enhanced PD is shown schematically in Fig. 3(a). A straight bus waveguide is laterally coupled with the microdisk to couple input light into the microdisk. A vertical PIN diode with P + doping region on the surrounding slab and N + doping on top, is integrated with the waveguide-coupled microdisk to extract the photo-generated current under reverse bias. The peak P + and N + doping concentrations are 2.0×10^{20} cm^{-3} and 2.5×10^{20} cm^{-3}, respectively. The distance between the edge of P + doping region and microdisk edge is 1 μm. At reverse bias, this distance is much smaller than the width of depletion region and thus the effect of lateral voltage drop should be small enough. Compared with traditional normal incidence RCE PDs, microdisk can be easily fabricated by a single lithography and etching steps. The fabrication processes of the devices are as follows: The N + doping region was first formed by selective ion implantation of As. Then microdisk and bus waveguide were fabricated by electron-beam lithography (EBL) and dry etching, leaving a thin slab for electrical path. The etching depth is about 350 nm. Grating couplers were then fabricated on the input and output waveguides by EBL and dry etching to couple light in and out with single-mode fibers. After that, the P + doping region was formed on the slab by selective ion implantation of BF_2. A rapid thermal annealing was then performed to activate the dopants for 10 s at a relatively low temperature of 750 °C to avoid Si/Ge inter-diffusion [24]. This is critical to the PD operating at 1.55 μm since Si/Ge inter-diffusion can decrease the average Ge composition in Ge QDs, thus reducing the absorption coefficient at longer wavelength. 500-nm-thick SiO_2 cladding film was then deposited by plasma-enhanced chemical vapor deposition and contact holes were opened by EBL and a combination of dry and wet etching of SiO_2. At last, AlSi was thermally evaporated and lifted-off to form the electrodes. The SEM image of a fabricated PD is shown in Fig. 3(b), together with the image of waveguide-coupled microdisk before SiO_2 deposition in Fig. 3(c). The radius of the microdisk is 4 μm. The width of the bus waveguide is 550 nm. And the gap between the microdisk and bus waveguide is 150 nm.

3. Measurement results and discussions

The devices were first characterized by measurement of optical transmission and photo-current spectra. Light from a tunable laser (Santec, TSL-510) was launched into the bus waveguide through a single-mode fiber and grating coupler. The output light was extracted