High Performance Germanium Photodetectors Integrated on Submicron Silicon Waveguides by Low Temperature Wafer Bonding

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Abstract:

Silicon based photonics, widely pursued for the vision of integrating microphotonicics with microelectronics on the same chip, rely on high performance photodetectors for its realization. Germanium (Ge), due to its large absorption coefficient at near infrared frequencies, and its lower cost compared to III-V semiconductors, is perceived as the best candidate for onchip photodetectors. High performance Ge photodetectors integrated on silicon waveguides have been reported very recently. However, they require specified high temperature (≥ 700°C) epitaxial growth of Ge, which limits the process compatibility with microelectronics. Polycrystalline Ge photodetectors fabricated from low temperature (≤ 300°C) evaporation have also been reported, however, their efficiency is relatively low (~15%) due to the poor crystal quality. Here we report low dark current (~100 nA) and high efficiency (> 90%) single crystalline Ge photodetectors integrated on submicron silicon waveguides fabricated using a low temperature wafer bonding process, which enable onchip photonic interconnections.

Research Summary:

We use a waveguide integrated metal-semiconductor-metal (MSM) configuration as shown in Figure 1. Here a single crystalline Ge film is bonded on a submicron silicon waveguide with a thin SiO₂ layer for electrical isolation. Metal electrodes are placed on top of the Ge pad to confine the light horizontally and collect the photogenerated carriers. The small size of the silicon waveguide allows small electrode spacing and thus ensures high-speed operations.

The thin Ge film used here is a high quality single crystalline film transferred from a Ge bulk wafer by a low temperature wafer bonding and ion cut process. The processing temperature for our entire fabrication flow is maintained ≤ 400°C, below the 450°C limit for complementary metal oxide semiconductor (CMOS) backend processes. This would allow the integration of photonic circuits on top of a CMOS chip following the metallization steps of the microelectronic chip.

We first implanted a 4-inch Ge wafer with hydrogen ions and patterned silicon waveguides on a 4-inch silicon-on-insulator (SOI) wafer with electron beam lithography and inductively coupled reactive ion etching. A SiO₂ cladding layer was then deposited and planarized with chemical mechanical polishing (CMP) down to a thickness of approximately 40 nm. This oxide layer acts as the bonding interface and the electrical isolation layer between the Ge layer and the underneath silicon.

The wafers were bonded together at room temperature, and then annealed up to 400°C to split the thin Ge film above the implantation depth off from the bulk wafer. A second CMP process was then performed to reduce the Ge thickness. We then define the Ge photodetector pads on top of the silicon waveguides. Another PECVD SiO₂ cladding layer was deposited to cover the silicon.
waveguides to ensure efficient coupling with optical fibers. Vias for contact electrodes were then patterned and Ti/Au was deposited to form the MSM structures. The electrodes were then connected to Au contact pads located next to the photodetectors. Figure 2 shows scanning electron microscope and optical images of the device along the fabrication.

We measure a low dark current of ~ 100 nA, a high fiber accessed responsivity of > 0.4 A/W, and an estimated quantum efficiency of above 90% in our fabricated Ge photodetectors. We use a Keithley 2400 source meter to apply a bias voltage across the device and record the dark current. The photocurrent is measured by launching TE polarized light from an optical fiber into the silicon waveguides with nanotapers at the input end of silicon waveguides for efficient coupling. Figure 3(a) shows a typical response for a photodetector length of 30 µm. The dark current is measured to be approximately 100 nA for a bias voltage up to 4 volts. This dark current is considerably lower than the previous reported Ge photodetectors using a similar MSM configuration but epitaxially grown Ge. Figure 3(a) also plots the photocurrent under illumination with a 0.95 mW input for a wavelength near 1550 nm. A large signal to noise ratio (photocurrent to dark current) of ~ 3000 is observed with this illumination level. Figure 3(b) plots the spectrum of the measured fiber accessed responsivity. A value as high as 0.44 A/W is observed near 1527 nm. If corrected for the coupling loss from the fiber to the silicon waveguide (estimated to be ~ 3 dB) and the propagation loss of the 0.3 cm long silicon waveguide before the photodetector (estimated to be 45 dB/cm), the quantum efficiency is estimated to be above 90%. The roll off in responsivity after 1540 nm (corresponding to the band edge of Ge) is due to the decreased absorption of Ge and unwanted absorption due to the metal electrodes.

In conclusion, we demonstrate Ge photodetectors integrated on submicron silicon waveguides with a low dark current of approximately 100 nA, a fiber accessed responsivity of > 0.4 A/W, and an estimated quantum efficiency above 90%. Theoretical speed above 40 GHz should be reached with revised structural design. These photodetectors with high performances and full compatibility with the CMOS backend processes enable the vision of integrating microphotonics and microelectronics on the same chip.

References: