**Abstract:**

We demonstrate photodiodes in deposited polycrystalline silicon at 1550 nm wavelength with 0.15 A/W responsivity, 40 nA dark current, and gigahertz (GHz) time response [1]. Sub-band absorption is mediated by defects that are naturally present in the polycrystalline material structure. The material exhibits a moderate absorption coefficient of 6 dB/cm which allows the same microring resonator device to act as both a high-Q demultiplexing filter and a photodetector. The device offers an alternative to standard germanium-based photodetectors in the silicon photonic platform.

**Summary of Research:**

The crystalline silicon-on-insulator (SOI) platform enables modulation and low-loss waveguiding in the telecommunication wavelength bands centered at \(\lambda = 1.3\ \mu m\) and 1.55 \(\mu m\). These functions can be implemented due to the 1.12 eV bandgap of bulk crystalline Si which only produces significant linear absorption for \(\lambda < 1.1\ \mu m\). To add infrared photodetection to silicon photonic circuits, germanium can be integrated as an absorbing material in CMOS processing environments [2]. However, epitaxial growth of Ge on Si requires complex processing steps to manage the 4% lattice mismatch between the two crystals as well as a crystalline starting material.

It is known that silicon can generate photocarriers via sub-band absorption of light with \(\lambda > 1.1\ \mu m\) when defects are present that contribute energy states within the bandgap [3]. For integrated SOI devices, surface state absorption can produce a relatively low responsivity \(R = 0.036\ A/W\) in thin waveguides [4]. Jessop, Knights, et al. showed that the absorption can be further enhanced by distributing defects throughout the waveguide by ion implantation [5]. Other groups have shown improved responsivity and bandwidth, but all demonstrations to date have required single-crystalline SOI as a starting material.

Here we show photodiodes in polycrystalline silicon (polysilicon), a standard deposited material that can be integrated in the CMOS material stack. We have previously used polysilicon to build integrated optical filters and electro-optic modulators [6] for monolithic integration of optical functionality onto a microelectronic chip. The results presented here demonstrate that at least 12% of the propagation loss in these submicron polysilicon waveguides is due to sub-band absorption that generates useful photocarriers. Polysilicon can therefore be used for both the modulator and photodetector at the start and end of an optical link on a CMOS chip.

We design photodetectors with an integrated PIN diode to sweep out generated carriers and a ring resonator geometry to reduce the footprint. The fabrication is similar to [6] with a summary as follows. We use 3 \(\mu m\) oxide as a lower cladding, deposit 270 nm of high quality amorphous silicon by low pressure chemical vapor deposition (LPCVD), and crystallize the material into polysilicon by a furnace anneal in N\(_2\) at 1100°C to maximize the grain size. We perform moderate n-type phosphorus doping to an average concentration of 2 \times 10^{17} \text{cm}^{-3}.

Many of the dopant ions and donor electrons are trapped at the material grain boundaries. We pattern waveguides and resonators using e-beam lithography, etch the devices to leave a 40 nm slab for electrical access, and dope p+ and n+ contact regions. We clad the devices in silicon dioxide by plasma enhanced chemical vapor deposition (PECVD) and make electrical contact with nickel silicide and aluminum.
The device is shown in Figures 1 and 2. Input light is trapped in the device by constructive interference when an integer number of wavelengths fits inside the optical path length of the microring. When the light is on resonance, it travels multiple round trips around the resonator until some percent of it is absorbed to generate photocurrent and the rest is scattered away. This ratio of absorption loss to total loss gives the efficiency of carrier generation inside the device.

We determine the internal responsivity of the photodiode to be as high as 0.15 A/W. Figure 3 shows the transmission and measured current when we sweep the laser wavelength with a DC reverse bias on the device. Figure 4 shows the resonant photocurrent at -13 V. The optical power coupled into the resonator is 6.65 µW. We find a quality factor \( Q = 10,500 \) and a maximum photocurrent \( I = 0.975 \mu A \) corresponding to internal responsivity \( R = 0.15 \) A/W, or internal quantum efficiency of 12%. The microring device acts as a wavelength-selective photodetector which can both demultiplex and detect one wavelength of a WDM signal. This combined functionality is not possible in strongly absorbing materials where high loss would prevent the formation of a high-Q resonance. Based on the optical loss and the quantum efficiency we determine that at least 6 dB/cm of the device propagation loss is due to useful absorption. Finally using an external modulator, we have shown operation of the device at data rates up to 2.5 Gbps.

References:

Figure 1: Microscope image of device and input waveguide.
Figure 2: Cross-section schematic.
Figure 3: Transmission (top) and photocurrent (bottom).
Figure 4: Photocurrent vs. wavelength.