Integrated Silicon WDM Demultiplexer with Ultra-Low Capacitance and High Speed Germanium Photodetectors

CNF Project # 980-01
Principal Investigator(s): Michal Lipson
User(s): Long Chen

Affiliation(s): School of Electrical and Computer Engineering, Cornell University
Primary Research Funding: National Science Foundation
Contact: lipson@ece.cornell.edu, LC286@cornell.edu

Abstract:
We demonstrate waveguide integrated germanium detectors with capacitance as small as 2.4 fF and directly recorded impulse response as fast as 8.8 ps. Based on such detectors and cascaded silicon microring resonators, we also demonstrate a highly scalable wavelength division demultiplexing system that can potentially provide tera-bit/s (Tbps) bandwidth over a small area.

Summary of Research:
The tremendous growth in computer processing power due to microelectronics scaling requires a corresponding increase in communication bandwidth. Optical interconnects, particularly silicon-based integrated photonics, could overcome traditional limitations of electrical interconnects and enable this increase [1]. To achieve this goal, individual optical components such as lasers, modulators, switches, routers and detectors have been demonstrated [2-4]. For on-chip applications, detectors with very small capacitance and high speed, and their integration with wavelength-division multiplexing technology are crucial for low power, large bandwidth systems.

We use a waveguide integrated metal-semiconductor-metal MSM design optimized for small capacitance and fast response. Figure 1(a) shows a cross-sectional schematic of the device. The parallel electrodes MSM configuration and the very thin germanium layer (260 nm) give rise to very low capacitance. We calculated the capacitance for a 30 µm long detector to be 2.4 fF only, which allows a load resistance up to 1 kΩ for detector speed of 60 GHz, implying a high sensitivity. The two planar electrodes provide strong optical confinement and electrostatic field in germanium, ensuring efficient and fast collection of photo-generated carriers. Figure 1(b) shows the optical energy distribution for the fundamental TE mode. Figure 1(c) shows the electrostatic field distribution in germanium with 1 V bias. The good spatial overlap of optical mode and electrostatic field leads to very short carrier transit time. With an electrode spacing of 600 nm, the average transit time can be as short as 7 ps, corresponding to a bandwidth over 60 GHz.

We fabricated the detectors and demultiplexers at low temperature, compatible with CMOS backend processes. We started with a 4-inch silicon-on-insulator (SOI) wafer, and transfer a thin crystalline germanium film onto SOI through wafer bonding and ion-assisted layer-cutting technique [5]. The transferred Ge layer is thinned down to ~ 260 nm. We then patterned the germanium layer, silicon layer, and electrical connects subsequently.
We measured the detector impulse response of as short as 8.8 ps, shown in Figure 2(a), which ideally corresponds to a bandwidth of about 50 GHz. This was obtained by injecting a pico-second pulse from a fiber laser into a silicon waveguide terminated with a detector, and recording the temporal response of the photocurrent. Note that no deconvolution is performed to factor out the response of the measurement apparatus (e.g., the bias tee and sampler have rise time of 3 ps and 3.4 ps), suggesting that the detector intrinsic response should be faster than the value reported here. This is the fastest integrated germanium detector reported. We also demonstrated the detector operation with intensity modulated non-return-to-zero (NRZ) optical signal at 40 Gbps. The result is plotted in Figure 2(b). Despite some small pattern dependence, clean detection of the digit pattern is observed here.

Based on these detectors, we demonstrate a highly scalable wavelength-division demultiplexing system with cascaded silicon microring resonators. Figure 3(a) shows the device. Optical signals of various wavelength channels propagate along a silicon bus waveguide. Each microring resonator is designed to resonate at one of these wavelengths, and route only that channel from the bus waveguide to its drop port. Each dropped signal is then coupled to a broadband germanium photodetector. Here as a proof of concept we demonstrate a 4-channel demultiplexer with ~ 10 μm radius resonators. Figure 3(c) shows DC spectra recorded with detectors at the end of the bus waveguide (through port) and the four drop-ports. Clean separation of the four wavelengths is observed here with a channel-channel crosstalk of -25 dB. Each channel has a bandwidth of ~ 0.15 nm (19 GHz) with a spacing of ~ 1 nm. To confirm the capability of demultiplexing optical data, we injected NRZ optical signal centered at one of the channels into the bus waveguide and measured the drop-port detector response. Figure 3(d) shows an eye diagram for the 4th channel at 15 Gbps. This data rate is limited only by the resonance bandwidth here.

The demonstrated demultiplexer can be scaled to a bandwidth in the Tbps regime. Assuming 1 nm spacing, the resonance bandwidth can be broadened to 0.4 nm (50 GHz – the detector bandwidth) while maintaining -10 dB crosstalk. Higher-order resonators can also be used to create flat-passband and faster roll-off to reduce distortion and crosstalk. Also, the number of channels can be greatly enhanced with smaller resonators and larger FSR. Microring resonators with more than 50 nm FSR can be obtained, and therefore allow as many as 50 channels. Combining these optimized demultiplexers with our very fast, ultra-low capacitance detectors will ultimately lead to integrated receivers with 2.5 Tbps (50 × 50 Gbps) bandwidth, very low power consumption and small footprint.

References: