A hybrid silicon evanescent photodetector

Hyundai Park¹, Alexander W. Fang¹, Richard Jones², Oded Cohen³, Omri Raday³, Matthew N. Sysak¹, Mario J. Paniccia², & John E. Bowers¹

¹University of California Santa Barbara, ECE Department, Santa Barbara, CA 93106, USA
²Intel Corporation, 2200 Mission College Blvd, SC-12-326, Santa Clara, CA 95054, USA
³Intel Corporation, SBI Park Har Hotzvim, Jerusalem, 91031, Israel

Significant research effort in silicon photonics has focused on realizing individual optical components that are suitable for photonic integrated circuits, including active devices such as lasers, modulators, and photodetectors as well as passive waveguide devices. Photodetectors are one of the important components that convert optical signals into the electrical domain for further signal processing and data manipulation. Germanium waveguide photodetectors (WPD) have been demonstrated using selective growth on a silicon-on-insulator platform [1], and a SiGe WPD has been investigated to reduce the lattice mismatch experienced by Ge photodetectors [2] in the wavelength regime of 1.3 µm and 1.5 µm. The work presented here is a silicon evanescent waveguide photodetector utilizing AlGaInAs quantum wells as an absorbing region, covering a wavelength range up to 1600 nm with a quantum efficiency of 90 %. The materials and processing are compatible with the hybrid silicon photonic integrated circuit (PIC) technology platform which has already demonstrated lasers [3] and optical amplifiers [4].

The device is comprised of AlGaInAs quantum wells bonded to a silicon waveguide as shown in Fig. 1. As light propagates through the hybrid waveguide, it is absorbed in the III-V region, generating electron hole pairs which are swept away as shown with the three arrows in Fig 1a. The input to the photodetector is a passive silicon waveguide. At the junction of the hybrid waveguide and the passive silicon waveguide, the III-V region is tilted by 7º to reduce the reflection at the waveguide transition. The final III-V absorbing region length in the hybrid photodetector is 400 µm with a silicon waveguide width of 2 µm. An SEM image of the final fabricated hybrid photodetector is shown in Fig. 1b.

Figure 2 shows the measured TE spectral response with different biases. TE responsivity at 1550 nm is 0.31 to 0.32 A/W, and is roughly constant over a range of reverse bias conditions from 0.5V to 3V. At a reverse bias of 3 V the internal quantum efficiency is ~ 90 % at 1550 nm using the measured -5.5 dB fiber coupling loss. The TE material absorption coefficient is estimated to be 1594 cm⁻¹ at zero bias by measuring output power from a silicon output waveguide and using the calculated confinement factors. The edge of the spectral response is red-shifted with a higher reverse bias since the applied electric field increases the absorption at longer wavelength. Figure 3 shows the photocurrent output as a function of the coupled input power at 1550 nm with different reverse biases. The 1-dB saturation input power is 1.8 mW and 8.8 mW for 0 V and 1 V reverse bias, respectively. No output current saturation is observed beyond a reverse bias of 4 V for the available 14 mW of fiber coupled power. The dark current is typically 50 nA to 200 nA with a reverse bias range of 1V to 4 V, and breakdown occurs when the reverse bias exceeds 16 V. The dark current increases exponentially as reverse bias is increased and it indicates that the dark current is likely dominated by band-to-band tunneling. The 11 ohm series resistance is due to the thin InP n-layer and the contact resistances. The measured device capacitance with different reverse biases is shown in Fig. 4. The capacitance is 7.5 pF under zero bias and decreases down to 5.3 pF as the reverse bias increases. This large capacitance is mainly due to the large III-V mesa size (12 µm x 400 µm). The capacitance of the III-V mesa is calculated to be 3.8 pF with zero bias ignoring the air fringe capacitance. Moreover, two p-probe pads contribute an additional capacitance of 2.95 pF from a 450 nm thick SiNₓ layer (ε=7.5) sandwiched between the p-probe pad and the n-layers. The capacitance of the mesa and p-pad capacitance can be minimized by reducing the width and length of the III-V mesa, and changing the SiNₓ insulation layer to a several micron thick benzocyclobutene (BCB, ε =2.6) layer respectively. The bandwidth of the photodetector was measured to be 470 MHz at a reverse bias of 4 V with a 50 Ω termination. This agrees with an RC limited bandwidth of 480 MHz calculated from the measured series resistance and capacitance. Higher bandwidth can be achieved by minimizing the capacitance of the device and incorporating traveling wave electrode designs [5]. Figure 5 and 6 show the calculated quantum efficiency and band width of silicon evanescent traveling wave photodetectors. The bandwidth calculation includes the effects of the velocity mismatch between optical and electrical signal, impedance mismatch to 50 ohm transmission line, microwave loss and carrier transit time in the undoped absorber layers. The calculation shows more than 10 GHz bandwidth is achievable with more than 50 % quantum efficiency.

We thank Mike Haney, Jag Shah and Wayne Chang for supporting this research through DARPA contracts, W911NF-04-9-0001 and W911NF-05-1-0175.

Fig. 1. (a) Device cross section (b) A SEM image of a fabricated silicon evanescent photodetector.

Fig. 2. Spectral response for TE polarization.

Fig. 3. Saturation characteristics with different biases.

Fig. 4. Dependence of capacitance on reverse bias.

Fig. 5. Calculated quantum efficiency

Fig. 6. Calculated bandwidth of traveling waveguide photodetectors. Each color represents a different mesa width.