Near-Infrared Photodetector Enhanced by an Open-Sleeve Dipole Antenna

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Abstract: We present a dipole-antenna-enhanced Ge photodetector that shows 20 times photocurrent enhancement ratio between two orthogonal light polarizations at 1310 nm wavelength, and a spectral resonance characteristic of ~ half-wavelength antenna behavior.

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High power consumption is a key challenge that has to be addressed for any practical optical interconnects to electronic chips [1]. Small detector capacitance is particularly desirable because it can significantly lower the power consumption of high-speed optical receivers on-chip [2]. A photodiode can be made to have ~fF or lower capacitance by using a subwavelength active region which, however, could result in very low responsivity because of the diffraction limit of the light. This trade-off between capacitance and responsivity could be overcome if we could concentrate the incident light into the subwavelength volume of the active region. Light localized in the optical near-field around nanometallic structures has the potential of satisfying such a requirement because of the strong optical near field enhancement [3–5]. Recently a C-aperture-enhanced photodetector has been demonstrated at near infrared wavelengths based on this principle [6]. However, for easy integration and low capacitance, it is generally advantageous to design planar devices such as the metal-semiconductor-metal (MSM) detectors that are widely deployed in high speed optical receivers.

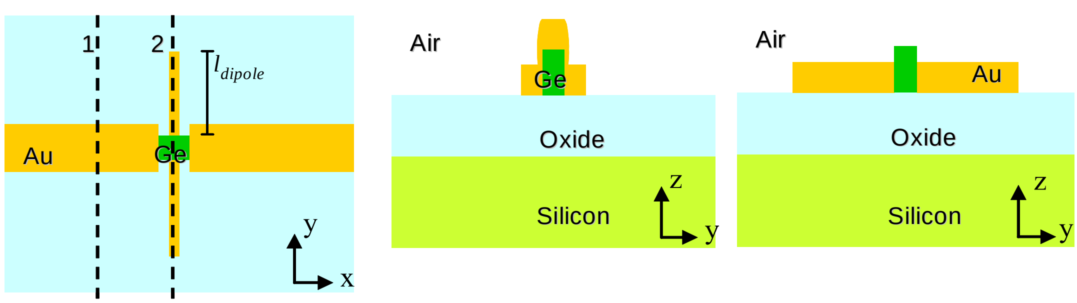
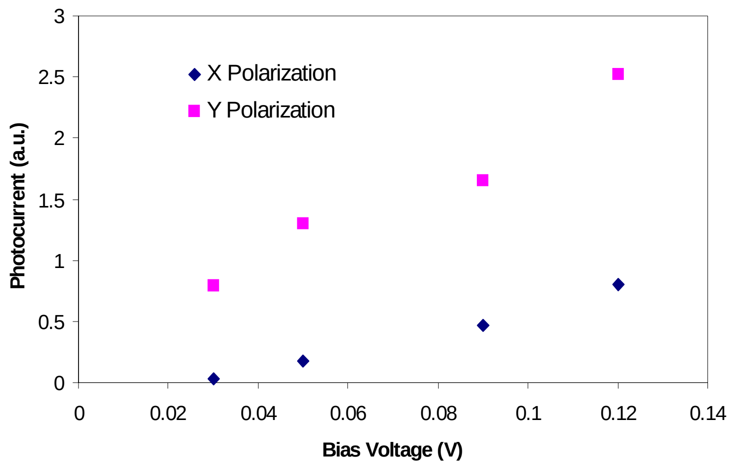
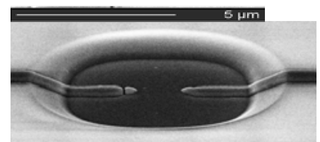


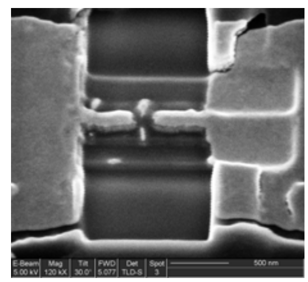
Fig. 1: Schematic of device. Left (top view): open-sleeve dipole antenna consists of a dipole antenna oriented in the *y* direction and two line electrodes ("sleeves") in the *x* direction. Middle (Cross Section 1): A Ge nanowire is underneath the two line electrodes. Right (Cross Section 2): Ge is in the gap region between two antenna arms.

In this approach, we propose an open-sleeve dipole antenna to enhance the photocurrent response of a subwavelength MSM photodetector. Fig. 1 shows a schematic of the device structure. The open-sleeve dipole antenna consists of a dipole oriented along the *y* direction and two line electrodes ("sleeves") along the *x* direction. A 60nm wide Ge nanowire lies underneath the two line electrodes and in the gap region between the two dipole arms. Open-sleeve dipole antennas were initially proposed [7] for radio-frequencies to increase the bandwidth of an ordinary dipole antenna. For our device, the dipole is used to collect light from a large area and concentrate it into the small subwavelength region of Ge. The sleeves are used to extract photocurrent without substantially changing the antenna characteristics of a bare dipole. Here, crystalline germanium is chosen to be the active material of our photodetector because of its high responsivity at near-infrared wavelengths and its compatibility with Si technology. Previous research has shown that the high dielectric constant of the substrate weakens the antenna resonant strength [6]. To avoid this effect, our detector is fabricated on a thick oxide layer. The Finite Difference Time Domain (FDTD) method is used to design and optimize the device size parameters. The dipole length determines the main resonance of the antenna. Because of the real metal properties at near-infrared frequencies, the first resonant antenna length is somewhat less than half a wavelength (half-λ). At 1310 nm wavelength the half-λ length is 435 nm for an ideal conductor taking into account the substrate effect, but the designed antenna resonant length using real metal properties is ~ 380 nm (two 160 nm arms plus the 60 nm gap). The distance between the two line electrodes is 150 nm.





Si seeding window and Ge line



SEM image of fabricated detector

Fig. 2. Bias voltage dependence of a dipole-antenna-enhanced photodetector for two orthogonal light polarizations at 1310 nm wavelength. The photocurrent when the light polarization is parallel to the dipole antenna (y polarized) is about 20 times higher than when it is perpendicular to them (x polarized) at 0.03V bias voltage.

Crystalline Ge-on-oxide is fabricated by the Rapid-Melt-Growth method on Si substrates[8]. We start with a clean Si wafer. 1 μm thick SiO_2 is then grown on Si by oxidation at 1100 °C. A Si seeding window is then opened in the oxide. 80 nm thick amorphous Ge is deposited using Low Pressure CVD, patterned and aligned to the Si seeding window. A thin layer of low-temperature oxide is deposited to encapsulate the patterned Ge lines. Rapid Thermal Annealing is used to heat the wafers up to 940°C for 2 seconds to melt the Ge. Ge crystalline growth starts from the Si (100)/Ge interface and propagates laterally through the Ge liquid on top of the oxide films. After the oxide etch, Ge nanowires with a width of 60 nm and length 2 μm are fabricated using an FEI Strata DB 235 FIB tool. Ti of 5 nm thickness and then Au of 45nm thickness are deposited using E-beam evaporation. The Ti layer is used to improve the adhesion of Au with oxide. Metal layers are patterned and lifted off to form the electrical contacts. Finally, the open-sleeve dipole antennas are shaped from the metal layer by FIB. The Scanning Electron Microscopy (SEM) images of the Si seeding window and antenna detector are both shown in Fig. 2.

The photocurrent from the detectors is measured using a lock-in amplifier with a modulation frequency up to 1.5 kHz. Light at 1310 nm wavelength is incident on the detector. Photocurrent is collected from the two line electrodes oriented in the *x* direction. The laser spot is focused to about 3 μm in diameter. We measure the polarization dependence of the photocurrent by rotating a half-wave plate in the optical path. The photocurrent reaches maxima when the light polarization is parallel to the dipole antenna (*y* polarized) and falls to minima when it is perpendicular to them (*x* polarized), as expected theoretically. The photocurrent of the device for incident light at *y*-polarization is measured to be 20 times that for *x*-polarization at very low bias voltage. The voltage bias dependence of photocurrent is shown in Fig. 2. This polarization dependent signal of the photodetector is direct evidence of an antenna effect in the near infrared. At higher bias voltage, the enhancement ratio is reduced to be about 3 times, possibly due to the collection of additional carriers generated by light that leaks into the region underneath the line electrodes.

Since the fields in that region are not enhanced by the antenna, the resulting photocurrent may have less polarization dependence, and the average photocurrent enhancement would therefore be lower at higher bias voltage. This effect could potentially be avoided if the Ge underneath the electrodes is removed, leaving only that in the gap region. More precise alignment techniques in the nanofabrication process are required to achieve this objective.

More information can be obtained by acquiring the detector's spectral response. A different detector with the same designed size parameters is used for this measurement. We measure the photocurrent response of the detector for y and x polarized light with laser tuning from 1350 nm to 1480 nm with a bias voltage of 0.03 volts. The ratio between the two photocurrent values is plotted in Fig. 3. The resonant peak at 1390 nm wavelength is also direct evidence of antenna behavior. This measured resonance is close to the designed resonant wavelength of 1310 nm.

In summary, a sleeve-dipole-antenna-enhanced Ge photodetector is presented that shows 20 times photocurrent enhancement at 1310 nm wavelength when the light polarization is rotated 90 degrees. The spectral response indicates that there is a resonant peak at 1390 nm wavelength with laser tuning from 1350 nm to 1480 nm. Both the polarization dependence and spectral response are direct evidence of antenna behavior at near infrared. In future work, we expect to measure the detector's projected picosecond response using the optical pump-probe method, and to integrate these devices for on-chip optical interconnects. This work was supported by the AFOSR "Plasmon Enabled Nanophotonic Circuits" MURI and the MARCO/DARPA FCRP Interconnect Focus Center.

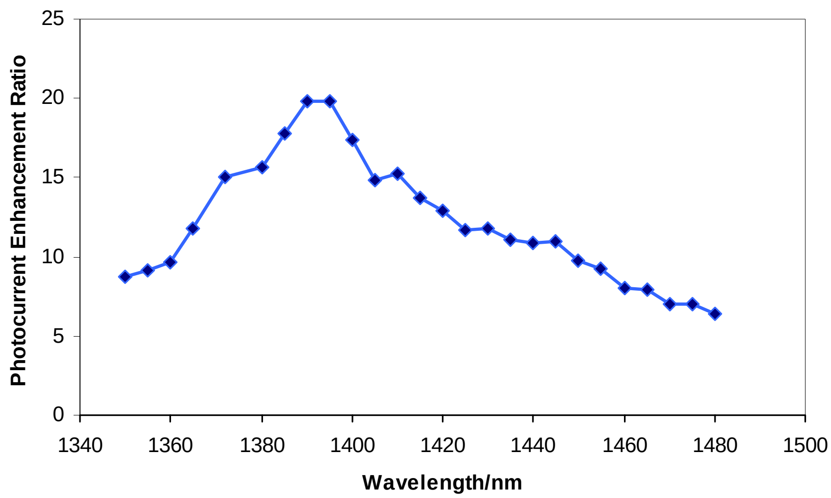


Fig. 3. Measured enhancement ratio between photocurrent for *y* and *x* light polarizations at 1350-1480 nm wavelengths.

References:

[1] D. A. B. Miller, "Rationale and Challenges for Optical Interconnects to Electronic Chips," Proc. IEEE **88**, 728-749 (2000).

[2] C. Debaes, A. Bhatnagar, D. Agarwal, R. Chen, G. A. Keeler, N. C. Helman, H. Thienpont, and D. A. B. Miller, "Receiver-less Optical Clock Injection for Clock Distribution Networks," IEEE J. Sel. Top. Quantum Electron. **9**, 400-409 (2003)

[3] P. J. Schuck, D. P. Fromm, A. Sundaramuthy, G. S. Kino, and W. E. Moerner, "Improving the Mismatch between Light and Nanoscale Objectives with Gold Bowtie Nanoantennas", Physical Review Letters, 94, 017402 (2005).

[4] J. A. Matteo, D. P. Fromm, Y. Yuen, P. J. Schuck, W. E. Moerner, L. Hesselink, " Spectral analysis of strongly enhanced visible light transmission through single C-shaped nanoapertures", Applied Physics Letters, 85, 648 (2004).

[5] T. Ishi, J. Fujikata, K. Makita, T. Baba and K. Ohashi, "Si Nano-Photodiode with a surface plasmon antenna", Japanese Journal of Applied Physics, Vol 44, No. 12, pp. L364-L366 (2005)

[6] L. Tang, D. A. B. Miller, A. K. Okyay, J. A. Matteo, Y. Yuen, K. C. Saraswat, and L. Hesselink, Opt. Lett. **31**, 1519 (2006).

[7] H. E. King, J. L. Wong, "An experimental study of a Balun-fed open-sleeve dipole in front of a metallic reflector," Journal of IEEE Transactions on Antennas and Propagation, Vol. AP-20, no.2, p.201-4 (1972).

[8] Y. C. Liu; M. D. Deal, J. D. Plummer, "Rapid melt growth of germanium crystals with self-aligned microcrucibles on Si substrates," Journal of the Electrochemical Society, v.152, no.8, p.G688-G693 (2005).