C-shaped nanoaperture-enhanced germanium photodetector

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Received January 12, 2006; accepted February 12, 2006; posted February 16, 2006 (Doc. ID 67215)

We present a C-shaped nanoaperture-enhanced Ge photodetector that shows 2–5 times the photocurrent enhancement over that from a square aperture of the same area at 1310 nm wavelength. We demonstrate the polarization dependence of the C-aperture photodetector over a wide wavelength range. Our experimental observation agrees well with finite-difference time-domain simulation results. © 2006 Optical Society of America

OCIS codes: 230.5160, 130.0250.

Chip-scale optical interconnects requires high-speed, low-capacitance, and Si-compatible photodetectors.[1] The speed of the photodiode is limited primarily by the transit time of photogenerated carriers to the electrodes and the depletion-layer capacitance of the semiconductor. Therefore the photodiode can be made intrinsically faster by use of a small active region. A subwavelength active region, however, could result in very low responsivity because of the diffraction limit. This trade-off between speed 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 about nanometallic structures has the potential of satisfying such a requirement because of strong optical near-field enhancement.[2–5] If we could use a localized interaction between the optical near field and a small semiconductor element, a high-speed response and sufficient responsivity could be achieved simultaneously.

Optical near fields associated with nanometallic structures have been studied extensively in recent years,[2–7] but little research has been done in the interaction of these strong near fields with semiconductors and the further transformation of the optical energy into electricity.[8,9] It was recently shown that the photogeneration of carriers in Si can be enhanced by use of a concentric grating structure as a surface plasmon antenna at 840 nm wavelength.[9] This method has the practical limitation that the entire grating structure necessary for exciting surface plasmon resonance occupies a large area in terms of wavelength. Alternatively, it was recently demonstrated that strong electromagnetic fields can be concentrated by use of resonant nanostructures locally without exciting long-range surface plasmon resonances.[10,11] The near-field intensity in these structures can be 2–3 orders of magnitude higher than the incident intensity. Thus there are opportunities for making densely integratable nanoscale photodetectors with both high speed and high responsivity if we can match these nanometallic antennas appropriately to semiconductor active structures. Because these photodetectors would have submicrometer size, they might have capacitance comparable with or smaller than state-of-the-art transistors and could thus possibly be monolithically integrated with VLSIs for efficient high-speed optical receivers.[12]

We use a C-shaped nanoaperture in a thin metal layer to enhance the photocurrent response of a subwavelength photodetector. The single C-shaped aperture, without any other supporting surface structures, provides a substantially higher resonant transmission than that of a conventional subwavelength square or circular aperture in a thin metal layer. It has been shown numerically that the near-field intensity in the C aperture is typically 2 orders of magnitude higher than the incident field intensity and that the light is effectively collected from an area many times larger than the physical area of the aperture.[13] Here, single-crystal Ge is chosen to be the active material for our photodetector because of its high responsivity at near-infrared wavelengths and its compatibility with Si technology.[14,15] In addition, a recent breakthrough in SiGe quantum-well modulators implies that Ge may become the material of choice for future integrated optoelectronics.[16]

To demonstrate the idea of a nanometallic-structure-enhanced photodetector, we designed a simple aperture experiment as described below. Figure 1 shows a schematic of the apertures and of the device's operation. The patterned Au film acts as the top electrode. Light at wavelengths of 1310–1540 nm is incident upon the aperture, and photocurrent is collected from the top and bottom contacts. The aperture samples are fabricated with an FEI Strata DB

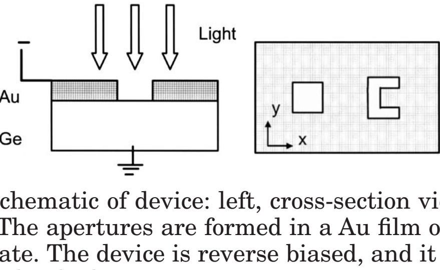

Fig. 1. Schematic of device: left, cross-section view; right, top view. The apertures are formed in a Au film on top of a Ge substrate. The device is reverse biased, and it functions as a Schottky diode.

235 focused ion-beam tool. A lightly n-doped Ge wafer is used as a starting substrate, and a thin film of SiO_2 is used as passivation after surface cleaning. Au of typically 100–200 nm thickness is deposited by e-beam evaporation onto the Ge surface through windows etched in the passivation layer. The thickness is chosen to be much larger than the skin depth at this wavelength, such that the metal is opaque; otherwise we could have large background photocurrents not associated with the light transmitted by the apertures. The Au film is then patterned by photoresist lift-off. The apertures are formed in the Au film by ion milling with 30 keV focused Ga^+ ions. Our experimental results show that approximately 20%–50% greater photocurrent is collected from a given area of a photodetector compared with the same structure patterned by traditional lithography. This is likely due to increased surface recombination owing to implanted Ga^+ ions. The fabricated sample is reverse biased, and its Schottky diode behavior is verified. The dark current density is $\sim 0.08\ \mathrm{nA}/\mu\mathrm{m}^2$, with -2 V bias.

For comparison, the photocurrent from a C aperture and that from a square aperture of the designed same area are measured by use of a chopped laser beam and a lock-in amplifier with modulation frequency up to 2 kHz. The laser spot from a diode laser is focused to approximately 2–3 μm in diameter. The photocurrent of the C-aperture detector is 2–5 times that of a square aperture of the same area at 1310 nm wavelength (Fig. 2). The measured C-aperture photocurrent is typically ~ 1 nA, with an illumination of 1.13 μW x-polarized light at 1310 nm wavelength. We measure the polarization dependence of the photocurrent, as shown in Fig. 2(c), by rotating a half-wave plate in the optical path. The C-aperture photocurrent reaches maxima when the polarization of the light is parallel to the two arms of the aperture (x polarized) and falls to minima when it is perpendicular to them (y polarized), as expected theoretically. This polarization-dependent signal of the C-aperture photodetector is direct evidence of an antenna effect in the near infrared. In contrast, there is no evident polarization dependence for the square-aperture detector. The C aperture used in this measurement has a smallest feature size of 60 nm. Both a schematic of the structure and a scanning electron microscopy image of the C aperture are also shown in Fig. 2.

One can obtain more information by acquiring the detector's spectral response. Figure 3 shows the photocurrent response of a C-aperture detector for two orthogonal polarizations with laser tuning from 1370 to 1540 nm. The photocurrent of the C-aperture detector is shown to increase slowly toward longer wavelength until 1500 nm. This increase for incident light at x polarization is more significant than that at y polarization. The big drop after 1500 nm is likely due primarily to the steep decrease in that region of the absorption coefficient of pure germanium.[15] The spectral response indicates that there may be a resonant peak in the antenna behavior at 1500 nm or longer wavelength.

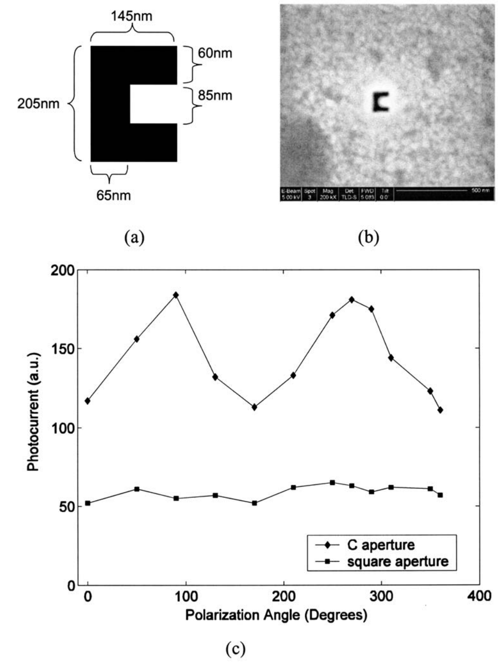

Fig. 2. (a). Designed C-aperture dimensions. (b). Scanning electron microscope image of the fabricated C-aperture in a Au film. (c). Polarization dependence of the C-aperture photodetector at 1310 nm wavelength. The C-aperture photocurrent reaches maxima when the polarization of light is parallel to the two arms of the aperture (x polarized) and falls to minima when it is perpendicular to them (y polarized). Solid curves connect data points as a guide for the eye.

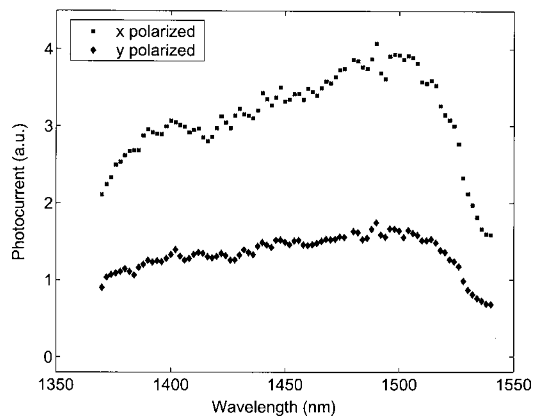

Fig. 3. Measured photocurrent spectrum of the C-aperture photodetector at two orthogonal polarizations of light. The C-aperture photocurrent shows a significant change over the wavelength range when the light is polarized parallel to the two arms of the aperture (x polarized).

To compare with experimental results, we perform finite-difference time-domain calculations for the near-field distribution of the aperture in the Au film at steady state. The grid size is chosen to be one tenth of the structure feature size. A Drude model is used to simulate real metal properties. The electric field amplitude in the vicinity of the C aperture is shown to be polarization dependent. When the incident light is polarized along the x direction, the electric field intensity in the aperture center can be more than five times that of the incident light. In contrast, the electric field intensity for the square aperture is always lower than the incident intensity. Therefore in the x polarization higher photocurrent can be collected from the C-aperture detector than from the square aperture of the same area. The fields in both C and square apertures decrease rapidly into the Ge and become negligible after 50 nm distance away from the aperture owing to their near-field nature. We perform a volume integration of the electric field intensity immediately below the aperture with 50 nm depth to estimate the relative photocurrents of different apertures. The volume integration value in the C-aperture case is approximately twice that for the square aperture of the same area. This theoretical photocurrent enhancement agrees well with our experimental observation.

The photocurrent enhancement could likely be improved by at least an order of magnitude by use of only a small Ge element instead of a bulk substrate, according to the same finite-difference time-domain model. The high dielectric constant of the substrate ($n=4.3$) has a significant effect on the response of the aperture photodetector. For one thing, it shifts the resonance significantly to longer wavelengths, which forces the resonant structure to be made smaller and thus to be more difficult to fabricate. For another, the overall resonant strength is theoretically weakened because there is a big index mismatch between the air and the semiconductor.

In summary, a nanometallic-structure-enhanced photodetector has been demonstrated in a proof-of-principle experiment. Even with a bulk Ge substrate, the C-shaped nanoaperture shows 2–5 times photocurrent enhancement over a square aperture of the same area. Our finite-difference time-domain simulation results agree well with the experimental observation. We have also demonstrated the polarization dependence of the C-aperture photodetector over a wide wavelength range. We expect to improve the resonant enhancement through the use of only a small Ge element and to optimize device structures for a high-speed, low-capacitance, and Si-compatible photodetector.

This research was supported by a Multi University Research Initiative (contract FA9550-04-1-0437) funded by the U.S. Air Force Office of Scientific Research. L. Tang was supported by an Office of Technology Licensing Stanford Graduate Fellowship.
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