Plasmonic device in silicon CMOS

L. Tang, S. Latif and D.A.B. Miller

The first plasmonic device integrated in Si CMOS, a C-shaped nanoaperture photodetector with a small feature size of 40 nm is presented. The photocurrent polarisation dependence of the C aperture detector is direct evidence of an antenna effect in the blue wavelength range. In contrast, there is no evident polarisation dependence for the square aperture detector with the same physical area. The photocurrent density of a CMOS detector is enhanced three times with the C-shaped nanoaperture.

Introduction: Plasmonics is a radically new device technology that has the potential to play a unique and important role in integrating optical devices with Si electronics on the chip level [1]. The light confinement with metallic nanostructures to dimensions comparable to electronic devices offers a potential solution to the size incompatibility problem between microscale dielectric photonic devices and nanoscale electronics [2]. Despite the explosive growth in the field of plasmonics, little work has been done in the context of integrating plasmonic devices on a realistic electronics platform.

Ag and Au are the most commonly used metals for plasmonic devices, but neither of them is compatible with CMOS processes. In search of alternatives, we calculate the permittivity values at visible wavelengths for Ag, Au and Al based on data in [3], as shown in Fig. 1. The real part of the permittivity is an indication of how the electrons are driven by the electromagnetic field. A large negative real part of permittivity is usually desirable for plasmonic devices owing to the small light penetration depth. As the wavelength decreases, the real permittivity decreases in magnitude for all the plotted metals, but that of Al remains very large, even in the blue wavelength range. The imaginary part of the permittivity represents the ohmic loss in the metal. Although Al is lossy at the red part of the spectrum, it has lower loss than Au at short wavelengths. This combination of a large negative real part and a small imaginary part of permittivity indicates that Al is a viable metal for plasmonics, especially at short wavelengths. Fortunately, current Si-based integrated circuit technology already uses Al nanostructures to route and manipulate electronic signals between and within transistors on a chip. This mature processing technology can thus be used to our advantage in integrating plasmonic devices with electronic circuits. Using Al metal, here for the first time, we demonstrate plasmonic devices on a commercial CMOS chip, paving the way for plasmonics to become the next wave of chip-scale optoelectronic technology.

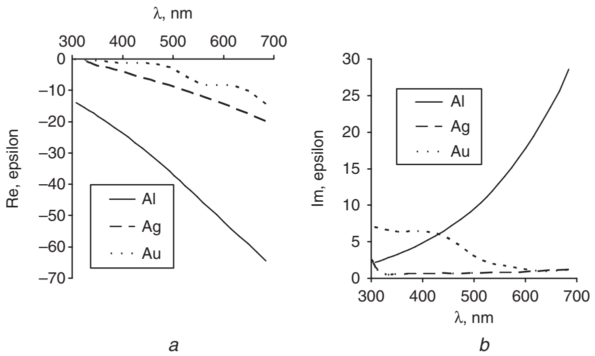

Fig. 1 *Calculated permittivity values of Ag, Au and Al*

a Real part
b Imaginary part

Fabrication: We have designed a test chip in a commercial silicon-on-sapphire CMOS process, developed by Peregrine Semiconductor. Full details about this process as a feasible platform for integrating photodetectors with CMOS electronics can be found in [4]. Fig. 2 shows a drawing of the side view and a picture of the top view of a typical photodetector on the chip. The 70 nm-thick active Si layer forms a lateral *pin* structure. The width of the intrinsic region between the heavily doped P^+ and N^+ contact areas is set by the finger spacing parameter. Multiple fingers are combined in parallel to extend the detector area in the lateral direction. We operate these detectors at blue wavelengths (425 nm). Since the absorption depth in silicon at that wavelength is approximately 180 nm, reasonable responsivity is possible under normal surface illumination. Most importantly, the absence of a semiconductor substrate results in extremely low capacitance devices. An 18×25 μm size detector with a finger spacing of 2 μm is calculated to have a capacitance of ~11 fF.

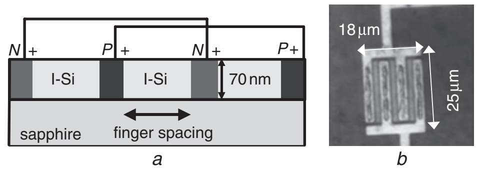

Fig. 2 *Cross-sectional and top view of original CMOS detector layout*

a Cross-sectional view of original CMOS detector layout
b Picture of top view

In this approach, we use Al nanostructures to enhance the photocurrent density of the *pin* detector. A resonant C-shaped aperture, without any supporting surface structures, can capture light from an area much larger than the physical area of the aperture, resulting in strong field enhancement in the aperture [5]. To fabricate such nanoapertures on-chip with the rest of the chip protected, we first open a hole in the protective nitride layer above the photodetectors using focused-ion beam (FIB) milling. After removing the top dielectric layers and exposing the interdigitated metal fingers, we use buffered HF to selectively etch the remaining passivation oxide until the intrinsic Si layer is exposed. Then Al of 150 nm thickness is deposited on Si. Finally, FIB is used to mill the nanoapertures in the Al layer. Fig. 3 shows a schematic of the cross-section and the SEM image of the final device. In the centre of the SEM image is the nanoscale C-shaped aperture, which is located approximately 1 μm lower than the top surface of the metal fingers.

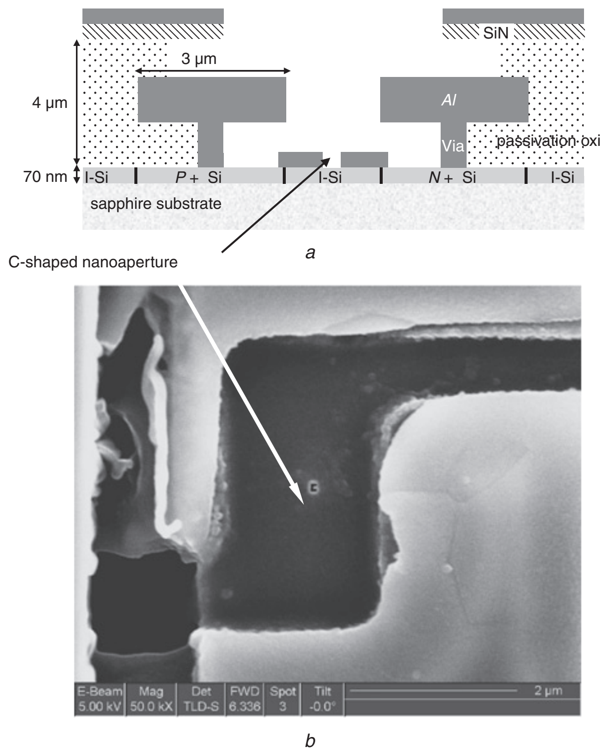

Fig. 3 *Cross-section schematic and SEM image of final device*

a Cross-section schematic of final device
b SEM image of final device

Results and discussion: The photocurrent from a C aperture with a small feature size of 40 nm (Fig. 4*b*) and a square aperture of the same designed area (Fig. 4*c*) are measured using a chopped laser beam and a lock-in amplifier. An 850 nm short-pulse laser is used to generate the 425 nm incident beam through second-harmonic generation. The laser spot is focused to about 11 μm in diameter. We measure the polarisation dependence of the photocurrent by rotating a half-wave plate in the optical path. As illustrated in Fig. 4*a*, the photocurrent from the C aperture reaches a maxima when the light polarisation is parallel to the two 'arms' of the aperture (*y*-polarised) and falls to a minima when it is perpendicular to the two 'arms' (*x*-polarised). This polarisation-dependent signal of the C aperture detector is direct evidence of an antenna effect in the blue wavelength region. In contrast, there is no evident polarisation dependence for the square aperture detector. The photocurrent of the C aperture detector for *y*-polarised light is measured to be four and a half times that of the reference square aperture detector.

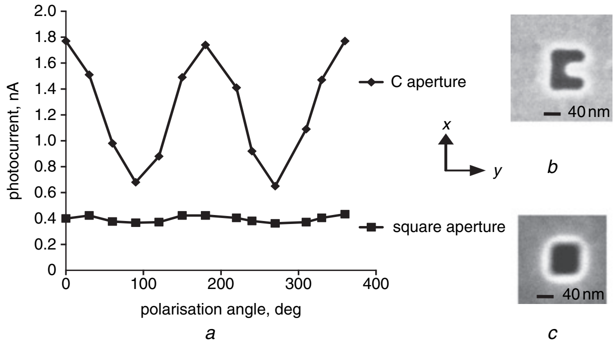

Fig. 4 *Photocurrent polarisation dependence and SEM images of C-aperture and reference square aperture*

a Photocurrent polarisation dependence
b SEM image of C-aperture
c SEM image of reference square aperture

Photocurrent per unit area is an important figure of merit in the integration of photodetectors with digital circuits. Fig. 5 displays the bias dependence of photocurrent per unit area for both the C aperture and the original large *pin* detector. In each scenario the photocurrent is normalised by the area of the intrinsic Si illuminated by the laser beam. The bias characteristics of the *pin* junction with the C aperture have changed, this is likely to be due to the addition of the Al layer on the intrinsic Si. The C aperture photodetector with *y*-polarised light shows three times higher photocurrent density than the large *pin* detector. This indicates that the nanoaperture-enhanced photodetector has actual advantages over a large detector when photocurrent density is important. At a higher bias voltage, the polarisation contrast is reduced, possibly owing to the collection of additional carriers generated by light that leaks into the region underneath the metal fingers. This effect could potentially be avoided with a better integration scheme. The high-speed response of the CMOS photodetector is verified by the optical pump-probe technique [4]. Shown in the inset of Fig. 5 is the transit-time-limited response of 31 ps for a detector with 1.2 μm finger spacing, corresponding to a bandwidth of 17 GHz. The advantages of higher photocurrent density from nanoapertures can become practically more useful as the size of the *pin* detector scales to nanoscale for higher speeds and lower capacitances.

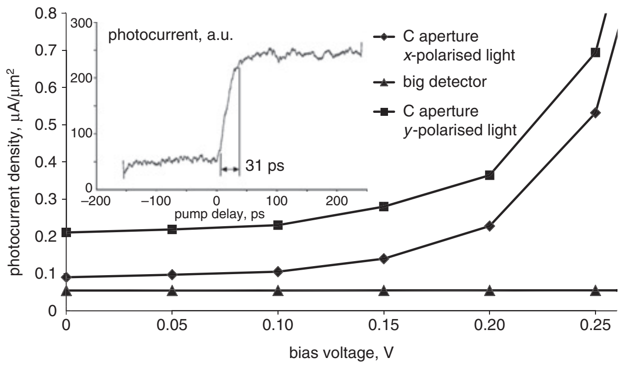

Fig. 5 *Bias dependence of photocurrent density*

Inset: Transient response of photodetector with 1.2 μm finger spacing

Conclusion: For the first time we demonstrate plasmonic effect in Si CMOS. The photocurrent density of a CMOS detector is enhanced three times with a C-shaped nanoaperture in Al metal. Such plasmonic devices offer the promise of optoelectronic integration at the scale of transistor dimensions, and may lead to significant power, speed and area gains.

Acknowledgments: This work was supported by the AFOSR 'Plasmon Enabled Nanophotonic Circuits' MURI programme, the MARCO/DARPA FCRP Interconnect Focus Center, and the DARPA/NSF PTAP programme.

26 March 2009
doi: 10.1049/el.2009.0839

L. Tang, S. Latif and D.A.B. Miller (*Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA*)

E-mail: luketang@gmail.com

References

1 Ozbay, E.: 'Plasmonics: merging photonics and electronics at nanoscale dimensions', *Science*, 2006, **311**, pp. 189–193
2 Tang, L., Kocabas, S.E., Latif, S., Okyay, A., Ly-Gagnon, D., Saraswat, K., and Miller, D.A.B.: 'Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna', *Nature Photonics*, 2008, **2**, pp. 226–229
3 Palik, E.D.: 'Handbook of optical constants of solids' (Academic Press, 1991)
4 Latif, S., Kocabas, S.E., Tang, L., Debaes, C., and Miller, D.A.B.: 'Low capacitance CMOS silicon photodetectors for optical clock injection', *Appl. Phys. A*, 2009, **95**, (4), pp. 1129–1135
5 Tang, L., Miller, D.A.B., Okyay, A.K., Matteo, J.A., Yuen, Y., Saraswat, K.C., and Hesselink, L.: 'C-shaped nanoaperture-enhanced germanium photodetector', *Opt. Lett.*, 2006, **31**, p. 1519