Vertical waveguides integrated with silicon photodetectors: Towards high efficiency and low cross-talk image sensors

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We describe the experimental realization of vertical silicon nitride waveguides integrated with silicon photodetectors. The waveguides are embedded in a silicon dioxide layer. Scanning photocurrent microscopy is performed on a device containing a waveguide, and on a device containing the silicon dioxide layer, but without the waveguide. The results confirm the waveguide’s ability to guide light onto the photodetector with high efficiency. We anticipate that the use of these structures in image sensors, with one waveguide per pixel, would greatly improve efficiency and significantly reduce inter-pixel crosstalk. © 2012 American Institute of Physics. [doi:10.1063/1.3678019]

There has been a recent upsurge in the use of complementary metal oxide semiconductor (CMOS), rather than charged coupled device (CCD), technology for image sensors. CMOS image sensors offer low power consumption, compatibility with CMOS logic technology, permitting random access of image data, and circuit integration.1–3 Increasing circuit complexity can come at the cost of optical performance, however. This is because increasing the number of metal interconnect layers enlarges the distance between the microlenses and photodiodes, reducing light collection efficiency and increasing inter-pixel cross-talk. Here, we experimentally demonstrate vertical waveguides, termed “light pipes”, integrated with photodiodes. We anticipate that applying this approach to CMOS image sensors, i.e., forming light pipes in the dielectric stack between the microlenses and photodiodes, would mitigate the efficiency and cross-talk problems. We describe a fabrication process by which the light pipes, consisting of cylindrical silicon nitride (SiN₃) pillars surrounded by silicon dioxide (SiO₂), are integrated with lateral p-i-n silicon photodiodes. Scanning photocurrent microscopy confirms their waveguiding ability, and the results are in good agreement with ray-tracing analysis. Silicon nitride pillars have been previously produced using small metal particles,4 and have been suggested for solar cell applications.5 Light pipes for image sensors have been simulated,6 and demonstrated experimentally,7 but with vertical lengths ranging from only 2.2 to 4 μm, and achieved by stacking multiple etched sections.7 We previously demonstrated the fabrication of light pipes, but not integrated with photodetectors.8,9 We expect that the light pipes we describe could also be useful for applications such as optical interconnects.10

The means by which light pipes can improve the performance of CMOS image sensors is illustrated Fig. 1. In Fig. 1(a), a conventional CMOS image sensor is shown. Each microlens focuses light through the dielectric stack region onto the photodetector. Normally incident light is focused to the center of the photodetector (Fig. 1(a)). Due to the finite size of the photodetector (diameter D), there exists a maximum angle (ϕ₁) at which light can be incident and still collected (Fig. 1(a)). This is approximately given by ϕ₁ ≈ n (D/2f₁), where n is the microlens refractive index (assumed to be equal to that of the dielectric stack) and f₁ is its focal length. Fig. 1(b) illustrates the case where the light pipes are used. It can be seen that the maximum acceptance angle ϕ₂ ≈ n (D/2f₂) is larger, due to the fact that the microlens has a shorter focal length (f₂). Light pipes, therefore, present the opportunity to improve efficiency and reduce inter-pixel cross-talk. Additionally, the use of light pipes should enable increased flexibility in the layout of the metal interconnects, compared to conventional CMOS image sensors, for which one needs to avoid placing metal in the path of the light focused by the microlens onto the photodetector.

The fabrication process is summarized in what follows. We fabricated a lateral p-i-n photodiode on a silicon-on-

Fig. 1. (Color online) (a) Conventional CMOS image sensor. Case of light normally incident upon the sensor is shown for middle pixel: microlens (focal length f₁) focuses light onto center of photodetector. Largest angle (ϕ₁) at which light can be incident and still be focused onto photodetector (diameter D) is shown for right pixel. (b) CMOS image sensor with light-pipes. Each microlens (focal length f₂) focuses light onto lightpipe entrance, rather than onto the photodetector. Largest angle (ϕ₂) at which light can be incident and still be focused onto lightpipe entrance and detected by photodetector is depicted for right pixel.
insulator (SOI) wafer, and on it formed a metal layer with a circular opening (diameter \( \approx 5 \mu m \)) centered on the photodiode. This served to define the extent of the photosensitive region, in order to model the situation of Fig. 1. We then deposited silicon nitride (SiN\(_x\)) to a thickness of about 7.5 \( \mu m \) by plasma enhanced chemical vapor deposition (PECVD). Reactive ion etching (RIE), with 6 \( \mu m \) diameter Al disks as the etch mask, was then used to form SiN\(_x\) cylindrical pillars. We then deposited silicon dioxide (SiO\(_2\)) to a thickness of about 8.7 \( \mu m \), and smoothed the surface by chemical mechanical polishing (CMP). It should be noted that the thicknesses of the deposited SiN\(_x\) film can be regarded as nominal, being estimated from the deposition rate. A scanning electron micrograph (SEM) of a cross section of a completed device obtained by focused ion beam (FIB) milling revealed that the SiN\(_x\) pillar had a height of 7 \( \mu m \) and diameter of 5 \( \mu m \). The pillars of Fig. 2(a), produced for test purposes and not integrated with detectors, had heights of 7.4 \( \mu m \). We completed the device by opening contacts by etching the SiO\(_2\), evaporating metal, and performing wire bonding (Fig. 2(b)). On the same chip, we also fabricated photodiodes without the SiN\(_x\) light pipe. Optical microscope images of the light pipe-free and light pipe-containing devices are shown as Figs. 2(c) and 2(d).

We next characterized the fabricated devices. We first placed the devices in a probe station and an electrometer (Keithley 2400), and found the dark current to be \( \approx 0.3 \mu A \) for both device types (Figs. 2(c) and 2(d)) at a bias voltage of \(-0.2 \text{ V} \). This was the bias voltage used in the subsequent scanning photocurrent measurements. These were performed by placing the devices in a sample-scanning confocal microscope (WiTEC). The light from a fiber-coupled laser (\( \lambda = 532 \text{ nm} \)) was collimated, passed through a chopper, and input to an objective lens (NA 0.9, 100x magnification) to focus it onto the top surface of the device, which sat on a piezo-electric stage. The laser power from the objective lens was \( \approx 7 \mu W \). The devices were biased (Keithley 2400), and the current was measured with a lock-in amplifier, with the reference signal provided by the chopper. In this way, the photocurrent was extracted from the total current. The photocurrent was recorded as the devices were scanned, with the results shown as Figs. 3(a) and 3(b). It can be seen that high photocurrent resulted when the laser spot was centered over the lightpipe (Fig. 3(a)) or photodetector (Fig. 3(b)). High photocurrent was also seen to result when the laser spot was centered over the mesa isolation trenches, but this does not affect the analysis of the light pipe properties. The photocurrent was considerably higher for the light pipe device than the device without the light pipe. As we describe below, this is consistent with the predictions of ray tracing calculations. The results confirm that the light pipe acts as a waveguide in guiding light from the top surface of the device to the photodetector.

In Fig. 3(c), the photocurrent signals, for the devices with and without the light pipes, are plotted as a function of distance along the cross sections indicated in Figs. 3(a) and 3(b). As noted above, these were obtained with the laser spot focused on the top surface. It can be seen that the light pipe device had a peak photocurrent \( \approx 6.3 \) times larger than the peak photocurrent measured for the device without light pipe. It can be seen, however, that local minima occur in the center of the experimental photocurrent profiles for the light pipe and light pipe-free devices. If we compare the photocurrent measured with the laser spot centered on each device, i.e., within the local minima, then the ratio is \( \approx 4.2 \) times. The cause is not fully understood, and will be the subject of future investigations. To understand why the photocurrent is higher for the light pipe device, we performed ray-tracing analysis.\(^{11}\) The analysis predicted that the photocurrent for the light pipe device is \( \approx 3.6 \) times larger than that of the device without light pipe, in agreement with the trend observed experimentally.

To characterize the light pipes further, we performed photocurrent measurements in which the device was scanned in the vertical (z) direction (Fig. 3(d)). The photocurrents were higher than before because the laser power was increased (25 \( \mu W \) from objective). The laser spot was centered over the light pipe, or over the metal detector for the light pipe free device, and the photocurrent measured as the piezoelectric stage was translated. Here, \( z = 0 \mu m \) corresponds to the laser spot being at the surface, and \( z = 6 \mu m \) correspond to the stage being moved 6 \( \mu m \) so that the laser...
spot is within the device. It can be seen that, for the light pipe device, the photocurrent reaches a maximum at $z = 1 \mu m$, and decreases as $z$ is increased. This is due to the coupling to the lightpipe being largest when the laser is focused at its entrance. From Fig. 3(d), it can be seen that the light pipe device photocurrent decreases as the vertical position is varied from $z = 0$ to $z = 6 \mu m$. The photocurrent is $\sim 1.3$ times higher when $z = 0 \mu m$ than when it is $z = 6 \mu m$. Ray tracing analysis predicts a ratio of $\sim 1.2$ times. For the light pipe-free device, it can be seen that the photocurrent signal increases $\sim 1.9$ times as the position is varied from $z = 0$ to $z = 6 \mu m$. This is due to the beam waist being closer to the detector. This is also in reasonable agreement with ray tracing calculations which give a ratio of $\sim 2.3$. It should be noted that the ray tracing approach we employ is appropriate for the pillars we analyze, since these have diameters significantly larger than the wavelength. For narrower pillars, other approaches, such as full-field simulations (e.g., FDTD) would be needed.6

In conclusion, we have demonstrated the integration of vertical silicon nitride waveguides with silicon photodetectors. Scanning photocurrent microscopy measurements are found to be in reasonable agreement with ray tracing calculations. We anticipate that the use of similar structures in CMOS image sensors would result in significantly increased efficiency and decreased cross-talk.

Our current method is not CMOS image sensor (CIS) process compatible but in our group we already demonstrated the fabrication of SiN$_x$ light pipes in CIS compatible method.9

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11See supplementary material at http://dx.doi.org/10.1063/1.3678019 for ray tracing model.