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Integrated on-chip silicon plasmonic four quadrant detector for near infrared light

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The ability to accurately track light beams in a given space is highly desired for myriad applications e.g., laser cutting, welding, interferometry, sensing, optical tweezers, free space optical communications, and more. Typically, achieving this goal in the short wave infrared requires the use of a cumbersome and expensive InGaAs photodetector implemented as a four quadrant (4Q) device. In this paper, we experimentally demonstrate an attractive approach by implementing a cost effective novel silicon based plasmonic 4Q photodetector. Our 4Q photodetector is implemented using a CMOS compatible plasmonic enhanced IPE Schottky photodetector and can operate in the short wave infrared band, where conventional silicon photodetectors cannot detect light. We have demonstrated the operation of the device and were able to accurately track optical beams of various beam waists at telecom wavelengths. The demonstrated device is based on standard materials and fabrication techniques which are common in the CMOS industry. As such, it provides an additional important example for the potential of plasmonics in the realization of chip scale novel devices which can be integrated with multiple other functionalities. Published by AIP Publishing.

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The field of plasmonics is gradually moving towards mitigating challenging applications in physics, engineering, chemistry, biology, medicine, materials science, environmental science, and more.1–3 One of the reasons for the flourishing of surface plasmon polaritons (SPPs) as an applied research topic is the ability to integrate several properties and functionalities in one chip with no need for using complex fabrication techniques and materials. On the one hand, SPPs offer important optical capabilities, e.g., light guiding,9,10 filtering,11–13 and beam focusing.14,15 On the other hand, SPPs also provide interesting electronic features such as light detection and electrical signal guiding.16–20 These combinations of optical and electrical capabilities are inherent in the case of plasmons because the metal-dielectric interface is used.

One of the applications that could potentially benefit from SPPs is the ability to precisely determine the position of a light beam relative to a surface. Typically, to determine the position of a beam of light, one would use a structure known as a four quadrant (4Q) detector, in which four photodetectors are closely integrated. By comparing the photocurrent in each of the four photodetectors, the beam position can be found. In this work, we design, fabricate, and characterize a plasmonic 4Q photodetector and demonstrate its capabilities. This device combines electric and photonic properties—light guiding, focusing, and photodetection. The device is implemented in standard complementary metal oxide silicon (CMOS) technology and is operated in the short wave infrared (SWIR) regime. As such, it can be used as a cost-effective solution which allows accurate beam positioning at the SWIR, even for wavelengths above the detection cutoff of silicon.

To find the relative position of a light beam, an apparatus known as a four quadrant (4Q) photodetector is commonly used. The 4Q detector consists of four closely spaced photodetectors. Four detectors are needed to grasp information regarding the beam position in each axis (positive and negative directions of the x- and y-axes). In commercial products (such as Ref. 21), a 4Q detector is implemented using volumetric or PN junction photodetectors. In the latter case, each photodiode takes the shape of a quarter of a circle. So, the photocurrent is generated all over the detector area. The position of the beam relative to the center of the 4Q detector can be found using

\[
x_{\text{pos}} \propto \frac{(I_1 + I_2) - (I_3 + I_4)}{I_1 + I_2 + I_3 + I_4}, \quad y_{\text{pos}} \propto \frac{(I_1 + I_3) - (I_2 + I_4)}{I_1 + I_2 + I_3 + I_4},
\]

(1)

where \(I_j\) is the current from the \(I_j\)th detector and the axis origin is at the center of the 4Q detector.

In this work, we demonstrate numerically and experimentally a 4Q photodetector at the wavelength of 1.55 \(\mu\text{m}\). Our 4Q photodetector is implemented by the concept of the plasmonic-enhanced Schottky photodetector based on the internal photoemission (IPE) process. Such photodetectors are the subject of extensive research over the last few years.1,9,22–32 The operational principle of our device is as follows. Light impinges on the device and can couple to SPPs at the metal edges in two regions (i.e., it can be coupled through edge A and/or edge B, Fig. 1(a), depending on the beam position). By the IPE process, hot electrons are generated in the metal. These electrons can overcome the Schottky barrier and be collected as a photocurrent in the

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of the beam position) can be found by convolving the beam profile with the metal edge. The metal edge is modeled as a delta function in one direction (e.g., y-direction) and as a rectangular in the other direction (e.g., x-direction). The expected current profile of each photodetector can be written as

$$I_j(x,y) \propto \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E_{in}(\tau_x, \tau_y)|^2 (rect_x(x - \tau_x) + \delta(y - \tau_y)) d\tau_x d\tau_y$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{2}{\pi \omega_0^2} e^{-\frac{1}{2}(\frac{x^2}{\omega_0^2})} (rect_x(x - \tau_x)) + \delta(y - \tau_y)) d\tau_x d\tau_y$$

$$= \frac{1}{\sqrt{2\pi \omega_0}} e^{-\frac{1}{2}\left(\frac{x^2}{\omega_0^2} + \frac{y^2}{\omega_0^2}\right)} \left(\text{erf}\left(\frac{\sqrt{2}(x+0.5w)}{\omega_0}\right) - \text{erf}\left(\frac{\sqrt{2}(x-0.5w)}{\omega_0}\right)\right),$$

where $y_j$ is the position of the photodetector, $\omega_0$ is the beam waist, $w$ is the width of the silicon detector [see Fig. 1(b)], and $I_j$ is the normalized current of the jth photodetector (i.e., $I_j = \frac{I_{j,max}}{I_{max}}$).

The position in each direction (e.g., y-direction) can be extracted using

$$I(x,y)_{y} \equiv I_j(x,y) - I_i(x,y)$$

$$\propto \frac{1}{\sqrt{2\pi \omega_0}} \left( e^{-\frac{x^2-0.5w^2}{\omega_0^2}} - e^{-\frac{y^2-0.5w^2}{\omega_0^2}} \right)$$

$$\times \left(\text{erf}\left(\frac{\sqrt{2}(x+0.5w)}{\omega_0}\right) - \text{erf}\left(\frac{\sqrt{2}(x-0.5w)}{\omega_0}\right)\right).$$

Using Eqs. (2) and (3), the current map [i.e., $I(x,y)$] of the device can be generated as a function of the beam waist and the spacing between the photodetectors. By comparing the measured map to the simulated map, the position of the beam can be found.

To have an insight into Eqs. (2) and (3), we plotted (Fig. 2) the expected current maps for different beam waists [according to Eq. (3)].

From Fig. 2, it is clear that in order to have sufficient information to find the position of the beam, the spacing between the two photodetectors should be less than then the beam diameter $2\omega_0$, i.e., $d > 0.5w$, where $d$ is the spacing between the photodetectors [see Fig. 1(b)]. In this case, when the beam is between the two photodetectors, the photocurrent varies almost linearly with the beam position.

It should be noted that in general the expected photocurrent magnitude does not vary linearly along the beam cross section. As so, the sensitivity, i.e., the change in current relative to the change in the beam position, is not constant. The sensitivity can be found by taking the derivative of Eq. (3) relative to the beam position.
The maximal sensitivity is obtained at the center of the device for $\frac{d}{2} > 0.5$.

The calculated photocurrent from the pincushion structure (point B in Fig. 1) is significantly lower (two orders of magnitude smaller) as compared with that of the edge coupling. Due to the lower significance of this mechanism, it is discussed in more detail in the supplementary material.

The 4Q detector was implemented using a silicon on insulator (SOI) wafer. The silicon device layer (250 nm thick) was p-type boron doped $\frac{5}{1017} \text{cm}^{-3}$. To prevent electrical shorts and crosstalk between the detectors, four silicon islands were electrically isolated from the rest of the chip. This was realized by oxidation of the entire silicon layer except for the photodetector area, Fig. 3.

The oxidation was done using local oxidation of silicon (LOCOS) as follows. First, thermal oxidation ($\sim 60$ nm) followed by plasma enhanced chemical vapor deposition (PECVD) of silicon nitride ($\sim 155$ nm) was performed. Next, the photodetector areas were defined using photolithography, followed by reactive ion etching (RIE) of the nitride, oxide, and 110 nm of silicon. The remaining silicon ($\sim 110$ nm) was oxidized, and four isolated silicon ribbons were created. The residual nitride was removed by wet etching. Using this LOCOS process, the silicon oxide was coplanar with the silicon islands. This planarization method was previously used in our group to create smooth and planar silicon waveguides.$^{17,34–36}$

Next, Ohmic contacts were created by electron beam evaporation of 200 nm of Al followed by annealing at 460°C for 30 min. Then, the Schottky contact was created by evaporating 40 nm of Al. The Schottky contact was common to all the photodetectors. Next, the subwavelength grating was formed using a focused ion beam (FIB). Finally, the device was mounted on a PCB and was electrically connected using wire bonding.

After fabrication, I-V measurements were performed to verify the operation of each of the diodes. A typical result can be seen in Fig. 4.

The experimental setup consists of a laser diode at the wavelength of 1.55 μm, connected to a pigtail lensed fiber (spot size of $\sim 2$ μm, Oz optics Ltd.), which illuminates the 4Q detector at a normal incidence angle. A quarter wave plate is placed between the lensed fiber and the sample to ensure that a circular polarization impinges on the sample. Circularly polarized light was chosen to verify equal coupling to surface plasmons in each of the four photodetectors.

![Fig. 3. The fabrication flow of the 4Q detector.](image)

![Fig. 4. I-V measurements of one of the Schottky diode photodetectors with (blue) and without (red) illumination, $\lambda = 1.55$ μm.](image)
The illumination beam position is fixed, while the position of the 4Q detector is scanned relative to the beam. The spot size of the illumination beam is controlled by varying the vertical distance (z-axis) between the 4Q detector and the fiber. The position of the 4Q detector relative to the beam is controlled using two motorized actuators (Thorlabs Z825b) perpendicular to the beam plane (xy plane). The current from each photodetector is measured using a source measuring unit (Keithley 2400). The current readout is recorded under a reverse bias of 1 V. Each measurement is repeated four times (i.e., scanning the position of the 4Q detector four times), whereas in each measurement, the photo-current of a different photodetector is recorded. The entire setup is controlled by the Labview program.

First, a beam of a relatively small waist, \( \omega_0 \approx \frac{\lambda}{24 \pi} \approx 3.5 \mu m \), is used to illuminate the 4Q detector. This small beam waist enables us to distinguish between the different detection areas in the 4Q detector (the edge detection and the pincushion structure, locations A and B in Fig. 1). The measured current map can be seen in Fig. 5.

From Fig. 5, it is apparent that a significant photocurrent is generated at the metal edge (position A at Fig. 1) while there is barely any photocurrent generation by the pincushion structure (position B at Fig. 1). This can be attributed to a low coupling efficiency of the plasmonic mode at the air-Al interface to the Si-Al plasmonic mode via the subwavelength grating. Additionally, during the fabrication process of the subwavelength grating, the FIB process might have damaged the silicon in the slit area and thus photocurrent generation has diminished.

Next, a beam with a larger waist, \( \omega_0 \approx \frac{30 \mu m}{24 \pi} \approx 0.5 \), was used to illuminate the 4Q detector. With this larger spot size, the 4Q detector can be operated as a position detector. The current map measurement can be seen in Fig. 6.

In Fig. 6, the superimposed current map from each of the diodes is presented. Unlike Fig. 5, we now obtain signal variations all over the device coordinates, including the region near the center of the device. This allows the extraction of the beam position relative to the 4Q photodetector (see Fig. 2) by comparing the measured current map to the simulated one [according to Eqs. (2) and (3)]. This is demonstrated in Figs. 7 and 8.

As can be seen in Fig. 7, there is a high similarity between the simulation and the measurements. This serves as an evidence for the validity of our approach. By matching the measured current map (top panel) to the simulated results (bottom panel), the beam position was extracted, as shown in Fig. 8.

As can be seen, a good agreement between the measured position and the values extracted from the actuators is obtained. Yet, the measured results show slight deviation from the linear fit. This can be attributed to the limited repeatability accuracy of our actuators (\( \sim 2 \mu m \)), which operate in an open loop mode. More accurate actuators which allow closed loop operation are expected to provide even better results.

In this paper, a novel nanoscale 4Q photodetector operating in the short wave infrared (SWIR) was designed, fabricated, and experimentally characterized at the wavelength of
1.55 μm. The 4Q photodetector is implemented using the plasmonic enhanced IPE Schottky photodetector and can operate in the SWIR band, where conventional silicon photodetectors cannot operate. In our design, two photocurrent generation mechanisms were implemented and tested (1) a metal edge and (2) a pincushion shaped structure. It was found that the pincushion shape contribution to the photocurrent generation was negligible, probably due to the low coupling of the plasmonic mode from the air-Al interface to the Si-Al and due to fabrication errors. However, the metal edge mechanism was found to be useful in extracting the position of the illumination beam relative to the 4Q photodetector. The device was tested under a normal incident angle. The study of the device response as a function of incident angle is the subject of future work.

The demonstrated device is based on standard materials (silicon and aluminum) and fabrication techniques which are common in the CMOS industry. As such, it provides an additional important example for the potential of plasmonics in the realization of chip scale novel devices which can be integrated with multiple other functionalities. We believe that such plasmonic based active photodetection devices can be used in myriad applications, e.g., laser cutting, welding, interferometry, sensing, optical tweezers, free space optical communications, and more.

See supplementary material for the calculated photocurrent from the pincushion structure.

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