Near-infrared sensitivity enhancement of silicon photodiode with plasmonic grating

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Abstract**—**We have proposed plasmonic diffraction for enhancement of near-infrared (NIR) sensitivity in a silicon-based image sensor. Metal grating efficiently diffracted incident light into the silicon absorption layer. The silver grating structure was fabricated on a large-area silicon photodiode by a lift-off method. The 1.2-fold improvement in sensitivity by plasmonic diffraction was demonstrated at a NIR wavelength of 940 nm.

I. INTRODUCTION

Near-infrared (NIR) image sensors are applied in Time-of-Flight (ToF) imaging, medical inspection, and night vision. Silicon-based NIR image sensors are attractive from the perspective of high spatial resolution, low energy consumption, and low fabrication cost compared to those based on III-V semiconductors. However, the NIR quantum efficiency (QE) is only a few percent, because silicon has a small absorption coefficient for NIR, and pixel size limits the depth of sensitive region to avoid high aspect ratio structure. Therefore, improving the NIR sensitivity independent of a silicon thickness is highly demanded.

Extending the effective propagation length in silicon has been proposed for improving NIR sensitivity. Refraction with a silicon pyramid surface and reflection with SiO_2 deep trench isolation (DTI) extended the propagation length and improved the NIR absorption efficiency to over 30% at a wavelength of 850 nm [1]. Similarly, scattering from a surface-limited local trench (similar to shallow trench isolation) array increased QE by 1.5 times at 940 nm [2].

Our group proposed a silicon-based back-side-illumination image sensor pixel with metal grating and metal-filled DTI as shown in Fig. 1 [3-5]. The metal grating diffracted incident light into the silicon side at a diffraction angle of approximately 90 degrees. The diffracted light was reflected at the metal DTI, resulting in an extension of the effective propagation length. By trapping the diffracted light within the silicon layer, NIR absorption efficiency was improved to 53% at wavelength 940 nm with 3-µm thick silicon. This enhancement was obtained by simulation. Here, we experimentally fabricated 2^{nd}-order silver gratings on silicon photodiodes and demonstrated the NIR sensitivity enhancement via plasmonic diffraction.

II. 2^{ND}-ORDER PLASMONIC DIFFRACTION

Surface plasmon resonance (SPR) is excited by matching the wave vector of the surface plasmon with that of the incident light. Under SPR, reflection light significantly decreases while absorption and scattering increase. At normal incidence, a diffraction grating is applied to excite SPR. The SPR wavelength is tunable based on the grating period.

Surface plasmon resonance (SPR) in the NIR region is excited in silver, gold, copper, and aluminum. In this research, silver was applied to the

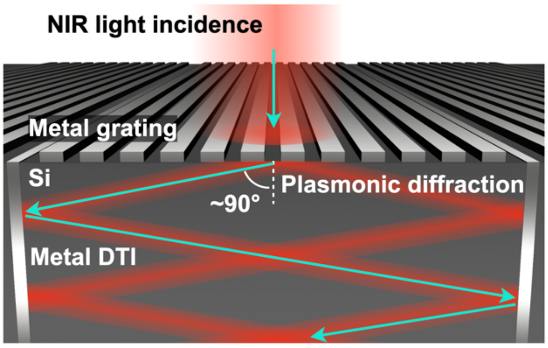

Fig. 1. Schematic image sensor pixel with metal gratings and metal-filled DTIs.

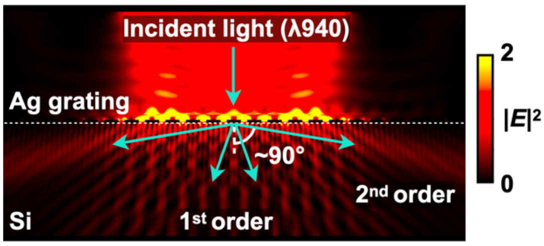

Fig. 2. Electric-field distributions of 2nd-order plasmonic diffraction.

plasmonic grating due to the lowest optical loss. We found effective diffraction at nearly 90 degrees into the silicon side under quasi-SPR, which is slightly shorter than the SPR wavelength [3]. As shown in Fig. 2, high-efficiency plasmonic diffraction was also achieved in the 2nd-order diffraction. In the figure, the light with a shallow angle represented the 1st-order diffraction, while the light with a larger angle represented the 2nd-order diffraction. By incorporating 2nd-order plasmonic grating into the image sensor pixel, we achieved a silicon absorption efficiency of 49% at a wavelength of 940 nm with a silicon thickness of 3.25 µm in simulation [5].

III. NEAR-INFRARED SENSITIVITY ENHANCEMENT

We demonstrated the NIR sensitivity enhancement in silicon photodiode incorporating the 2nd-order silver gratings. The 2nd-order silver gratings are fabricated with moderate patterning accuracy due to their larger period and width compared with the 1st-order. Table 1 summarizes the plasmonic grating fabrication process. A silicon photodiode was coated with a 400 nm thick electron beam (EB) resist, ZEP520A. Using the EB lithography system ELS-7800, stripe patterns were drawn on the resist with a dose of 120 µC/cm^2. Since ZEP520A is a positive resist, the unexposed regions of the resist remain. After EB exposure, the exposed resist was developed with o-xylene. A 130 nm thin silver film was deposited by vacuum evaporation on the photodiode with the resist pattern. After the deposition, the unexposed resist and silver on the resist were eliminated with Remover 1165 solution. To prevent degradation of the fabricated silver grating, PDMS (Polydimethylsiloxane) with a thickness of 150 µm was coated as a protective film. Fig. 3 shows SEM (Scanning Electron Microscope) images of the fabricated silver gratings. The silver gratings were fabricated as a one-dimensional array with a period (p) of 530 nm, a line width (w) of 380 nm, and a height (h) of 130 nm (Fig. 3(a)). In the case of the p530, the 2nd-order plasmonic diffraction angle is theoretically expected to be 80 degrees at a wavelength of 940 nm. The enlarged view in Fig. 3(b) shows that the silver grating has high precision in line width. The silver grating was fabricated with non-tapered sidewalls as shown in Fig. 3(c) of the cross-sectional view.

Table 1. Plasmonic grating process.

Process	Conditions	
Resist spin-coat	Resist	ZEP520A
	Thickness	400 nm
EB exposure	Equipment	ELS-7800
	Dose	120 µC/cm^2
Development	Solution	o-Xylene
Silver deposition	Thickness	130 nm
Lift-off	Solution	Remover1165
Protective film	Material	PDMS
	Thickness	150 µm

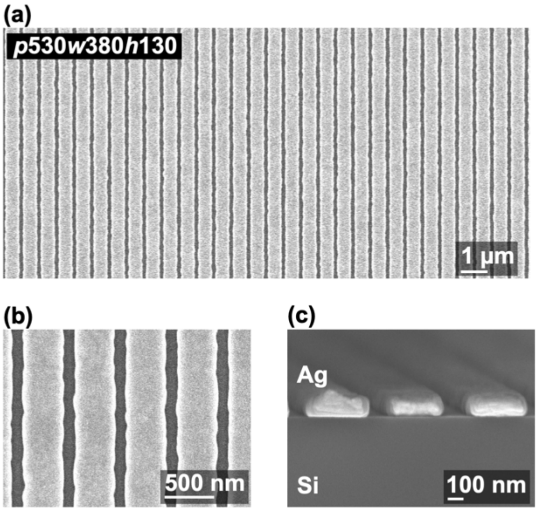

Fig. 3. SEM images of fabricated silver grating. (a) One-dimensional array, (b) enlarged view, and (c) cross-sectional view.

Figure 4 shows a schematic diagram of the optical system used for measuring the sensitivity of the photodiode. Monochromatic light was selected from the white continuum laser and irradiated to the photodiode. The incident polarization was controlled by a Gran-Tompson prism. A CCD camera and a lamp were used for aligning the laser incident light to focus on the silver grating pattern. The photocurrent of the photodiode was measured by a system source meter, Keithley 2636B.

The silver grating with a pattern size of 100 µm × 100 µm was fabricated on a photodiode with a large photosensitive area of 10 mm × 10 mm to demonstrate the plasmonic diffraction enhancement. The incident light was focused to approximately 10 µm diameter spot on the grating pattern. Figure 5 shows the current-voltage characteristics of silicon photodiode with/without the silver grating for TM

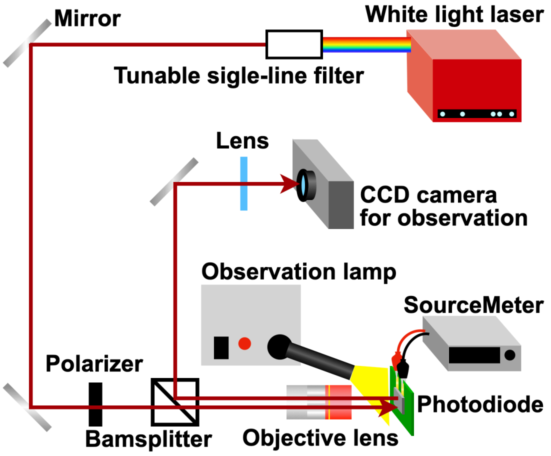

Fig. 4. Schematic diagram of the optical system used for measuring the sensitivity of the photodiode.

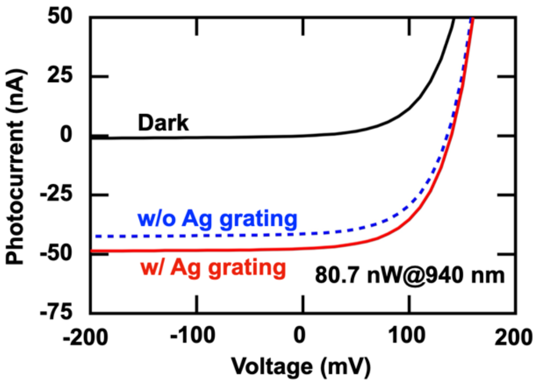

Fig. 5. Current-voltage characteristics of silicon photodiode with/without silver grating for TM-polarized incidence at wavelenght of 940 nm.

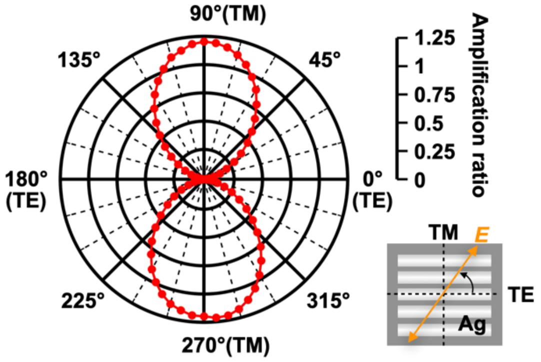

Fig. 6. Polarization dependence of NIR sensitivity amplification ratio at the peak wavelength.

(Transverse Magnetic)-polarized incidence with respect to the grating at a wavelength of 940 nm. Even with the incorporation of the silver grating, the photodiode electrical characteristics were maintained. The photocurrent with the silver grating was greater than that without the grating, which proved the NIR sensitivity enhancement by quasi-SPR.

Figure 6 shows the polarization dependence of the NIR sensitivity amplification ratio. The amplification ratio was defined as the ratio of sensitivity with the Ag grating to that without the grating. With the polarization angle increasing from 0 to 90 degrees, the amplification ratio raised from 0 to approximately 1.2. Similarly, from 90 to 180 degrees, the amplification ratio decreased from 1.2 to 0. This pattern demonstrated a periodic variation in the amplification over the full 360-degree range. This polarization extinction ratio is beneficial for active sensing applications like LiDAR. Efficiently detecting emitted TM-polarized light while suppressing randomly polarized ambient light, such as sunlight, enhances performance. The polarization angle of 0 degree corresponded to TE (Transverse Magnetic) polarization. In the case of the TE-polarized incidence, the Ag grating functioned as a reflective mirror because the oscillating electric-field of the incident light did not interact with its period. As a result, the sensitivity decreased compared to the case without the grating.

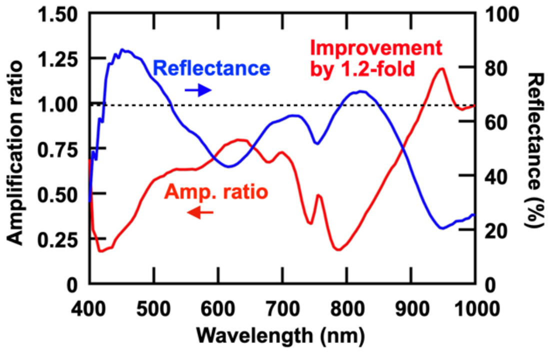

Fig. 7. Sensitivity amplification ratio and reflectance of the silver grating versus wavelength at TM polarized incidence.

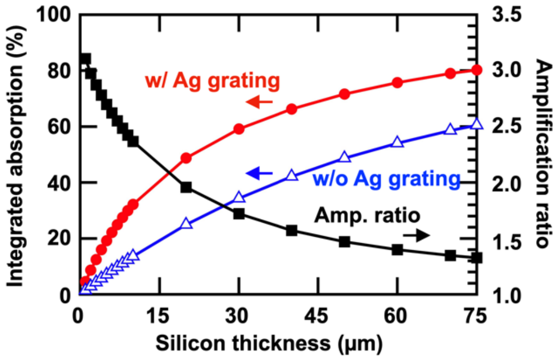

Fig. 8. Simulation results of silicon absorption efficiency and amplification ratio versus silicon thickness at 940 nm wavelength.

Figure 7 shows the reflection spectrum and the amplification ratio spectrum at TM polarized incidence. The wavelength range where the sensitivity improved corresponded to the reflection dip wavelength caused by SPR. The silver grating enhanced the sensitivity in the 925–965 nm range, reaching up to 1.2-fold at 940 nm compared to the sensitivity without the silver grating.

We simulated silicon absorption efficiency versus silicon thickness at 940 nm wavelength (Fig. 8). The silicon absorption with the silver grating was higher than that without the grating due to the extension of the effective propagation length by plasmonic diffraction. For Si thicknesses below 15 µm, the silicon absorption slope with the grating was steeper than that without it. This indicated that the absorption was mainly caused by the 2nd-order diffracted light at a large angle of 80 degrees. According to the spectral response measurement for the photodiode without the grating, the depletion layer thickness was estimated to be 75 µm. The amplification ratio of the silicon absorption with 75 µm, depletion layer thickness of the silicon photodiode, was assessed at about 1.35. The amplification ratio obtained from the experiment and simulation exhibited good agreement. A thinner silicon layer resulted in a higher amplification ratio, a 3-µm-thick silicon improving the absorption efficiency by a factor of 2.9. Therefore, by utilizing a depletion layer of just a few micrometers, as used in the silicon image sensors for visible light, plasmonic diffraction would significantly enhance the near-infrared (NIR) sensitivity.

IV. CONCLUSIONS

We proposed plasmonic diffraction for the enhancement of NIR sensitivity in a silicon-based image sensor. The 2nd-order silver gratings were incorporated with the silicon photodiode throughout EB lithography and lift-off processes. The incident NIR light was diffracted into the silicon side at an angle of 80 degrees. Therefore, the effective propagation length was dramatically extended compared to without the grating. An improvement of 1.2 times in NIR sensitivity was achieved at a wavelength of 940 nm with a 75 µm-thick depletion layer. Moreover, the significant enhancement of NIR sensitivity was simulated using a thin depletion layer of a few micrometers.

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