Angular selectivity of SOI photodiode with surface plasmon antenna

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Abstract A novel angle selective photodetector with gold surface plasmon (SP) antenna on a silicon-on-insulator (SOI) photodiode (PD) is proposed to capture the direction of the incident light. Two types of SP antenna, namely one-dimensional line-and-space grating and two-dimensional hole array grating, are reported. The SP antenna efficiently couples the incident light with the waveguide modes in the SOI PD at specific incident angles. The analytical modelling based on the phase matching between the diffracted light from the SP antenna and the propagating light in the SOI predicts the angle selective behavior of the device. The simulation by finite difference time domain (FDTD) method and measurement have successfully confirmed the prediction. These characteristics to detect the light at different incident angles could be useful in emerging applications such as lensless imaging.

Keywords: angle selective pixel (ASP), azimuth-elevation angular distribution, surface plasmon (SP) antenna, silicon-on-insulator (SOI) photodiode (PD), complementary metal-oxide-semiconductor (CMOS) technology

Classification: Integrated optoelectronics (lasers and optoelectronic devices, silicon photonics, planar lightwave circuits, polymer optical circuits, etc.)

1. Introduction

Recently, there is a growing interest in developing plenoptic imaging technology, in which more dimensions of information, such as polarization, wavelength, phase, light incident direction, etc. are utilized in addition to the ordinary information of light intensity and time elapsed [1]. Among these, the use of the information of incident direction (light field) has been researched intensively with a variety of applications such as post-capture refocus, depth of field (DOF) extension, range finding, lensless imaging, etc. [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] Historically, the detection of the light incident angles (capturing of the light field) was performed by the large system of an arrayed cameras [2, 3], but more recently has been realized in a compact way by placing optical elements such as pinhole array [4], microlens array [3, 5, 6], diffruser [7], special grating [8, 9, 10], etc. in front of the image sensor. Furthermore, better manufacturability and relaxed tradeoff between spatial and angular resolutions could be attained by the on-chip angle selective (sensitive) pixels (ASPs) [11, 12, 13, 14, 15, 16, 17, 18, 19]. Talbot pixels consisting of the stacked gratings with various phase shifts in their periods were successfully applied to the post-capture refocusing, range finding, etc. [11, 12, 13, 14, 15] Angular sensitivity of the single-layer polarization filter was also used together with the quadrature pixel cluster (QPC) to reduce the number of necessary sub-pixels [16]. Unique approach to utilize the optical coupling of two closely spaced Si nanowires was reported to realize the angular sensitivity as small as 0.32° [19]. Although most of the ASPs above are compatible with complementary metal-oxide-semiconductor (CMOS) technology, have good manufacturability, and have successfully been applied to advanced imaging, there are still some issues in the efficient use of the incident light. For example, it is reported that the ordinary Talbot pixel shows 88% reduction of the quantum efficiency compared to that of the bare pixel, and still the reduction is 55% even after the structure modification by the post-fabrication process [15]. Development of ASPs with high quantum efficiency, angle resolution, and manufacturability is keenly anticipated.

Our previous research demonstrated that the surface plasmon (SP) antenna of metal line and space (L/S) grating enhanced the quantum efficiency of silicon-on-insulator (SOI) photodiode (PD) when it is placed on top of the PD [20, 21, 22, 23, 24, 25]. The wavelength of the peak efficiency could be tuned by the L/S period [21, 22], and, similarly to the case with subwavelength hole array [26], the SP antenna realizes absorption efficiency in the PD larger than the aperture ratio (space/period ratio of the L/S grating) due to the enhanced coupling between incident light and the lateral propagation mode in the SOI slab waveguide [21]. The shift of the peak wavelength with respect to the incident angle was also observed [23, 24], but it was evaluated only for the elevation angle. Furthermore, we briefly reported the azimuth-elevation angular distribution of the quantum efficiency (light absorption efficiency in the PD) considering the possible use as ASPs for advanced imaging [25].

In the present work, we make a detailed evaluation of the azimuth-elevation angular distribution for the SOI PD with SP antenna based on the results of the theoretical estimation, numerical simulation and experiment. For the first time, the characteristics of the SP antenna with two-dimensional (2D) hole array grating are reported in addition to those of the one-dimensional (1D) L/S grating.

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2. Device structure and fabrication

The device structure of the proposed SOI-PD with SP antenna is shown in Fig. 1(a). The gold (Au) SP antenna of 1D L/S grating [Fig. 1(b)] or 2D hole array grating [Fig. 1(c)] is placed above the lateral p-n junction PD with SOI thickness $t_{SOI}$ of 100 nm. Au thicknesses $t_{Au}$ are 100 and 50 nm for 1D and 2D gratings, respectively, and titanium (Ti) adhesion layer with a thickness $t_{Ti}$ of 5 nm is inserted below the Au layer. The SOI layer of PD is sandwiched by the gate oxide layer ($t_{GOX} = 100$ nm) and the buried oxide layer ($t_{BOX} = 200$ nm), and functions as a slab waveguide to increase the optical path length for larger light absorption. The antenna primarily works as a grating coupler between the incident light and the propagating light in the SOI, and the separation between these is set by the $t_{GOX}$. The peak $t_{GOX}$, at which the quantum efficiency becomes maximum, changes with the grating period and the corresponding peak wavelength [21], and the $t_{GOX}$ of 100 nm is chosen to attain relatively high quantum efficiency at a wavelength of 685 nm used in this study. The SP antenna was named considering the contribution of localized surface plasmon (LSP), which was manifested by the quantum efficiency larger than the aperture ratio of the grating as pointed out in the Introduction. The antenna, which is electrically isolated by the gate oxide layer, also work as a gate electrode to maximize the volume of the depletion region in the SOI PD by adjusting the gate and substrate voltages, i.e. negative $V_G$ accumulates the top surface of the SOI with holes and positive $V_{SUB}$ inverts the bottom surface of the SOI with electrons, and vice versa, under an ideal condition [21]. Fig. 1(d) shows the configuration of the incident light. The incident direction is represented by azimuth ($\phi$) and elevation ($\theta$) angles. Polarization of light is set so that the magnetic field is parallel to the equi-$\theta$ line and x-y plane since the $E$ and $H$ are electric field and Poynting vector, respectively. $H$ is parallel to the equi-$\theta$ line and x-y plane.

The fabrication process of the metal-oxide semiconductor (MOS)-type SOI PD with SP antenna is as follows. (1) Thickness of the p– SOI layer of the commercial substrate is adjusted by oxidation and etching, (2) the SOI layer is patterned by photolithography and etching to define the PD areas, (3) cathode (n–) and anode (p–) areas are doped by ion implantations, (4) gate oxide layer is formed by oxidation and chemical vapor deposition (CVD), and (5) SP antenna is finally made by electron-beam (EB) lithography, deposition of metals, and liftoff. The optical and scanning-electron micrographs of the fabricated device are shown in Fig. 2. Note that the fabrication process above is compatible with the ordinary CMOS technology except for the use of Au, which will result in good manufacturability and the ease of integration with circuits.

3. Theoretical estimation of the directivity

The directivity of the SOI PD with SP antenna can be explained based on the phase matching condition between the diffracted light from the grating and the propagating light in the SOI slab waveguide as shown in Fig. 3 for the case of the light propagating in x direction. Since the incident light is tilted by $\theta_{xz}$, the elevation angle of $S$ projected on x-z plane, there is a phase shift $\Delta$ between the lights entering the adjacent metal lines in the grating given by

$$\Delta = \left(\frac{2\pi}{\lambda}\right) p \sin \theta_{xz}$$

(1)

and

$$\theta_{xz} = \tan^{-1}(\tan \theta \cos \phi),$$

(2)

where $p$ is the grating period and $\lambda$ is the wavelength in the free space. Due to this phase shift, different phase matching conditions arise for forward wave

$$\theta_{xz} = \sin^{-1} \lambda \left(\frac{1}{\lambda_{gb}} - \frac{1}{p}\right)$$

(3)

and for backward wave

$$\theta_{xz} = \sin^{-1} \lambda \left(\frac{1}{p} - \frac{1}{\lambda_{gb}}\right),$$

(4)
where $\lambda_{gf}$ and $\lambda_{gb}$ are respective propagation wavelengths in the PD (SOI slab waveguide). When the waves propagate in $y$ direction, $\theta_{yz}$ in place of $\theta_{xz}$ should be considered.

$$\theta_{yz} = \tan^{-1}(\tan \theta \sin \phi), \quad (5)$$

The propagation wavelength $\lambda_g$ in the SOI can be calculated by solving the transcendental equations [21, 27] under the assumption of infinite-thick oxide claddings (gate oxide and BOX). For a given $t_{SOI}$ and $\lambda$, the $\lambda_g$ is obtained, and then spatial pattern of $\theta$ and $\phi$ that satisfy the phase matching condition and expectedly give high quantum efficiency is obtained for a particular $p$ by solving Eq. (2) or (5) and Eq. (3) or (4). Note that Eq. (3) is applicable for $p > \lambda_g$, and Eq. (4) is for $p < \lambda_g$. Also note that 1D L/S grating can be an effective coupler only for the waves propagating in $y$ direction.

Fig. 4 shows the theoretical spatial patterns of the phase matching condition (high quantum efficiency locus) with respect to $\phi$ and $\theta$ for $t_{SOI} = 100$ nm and $\lambda = 685$ nm, which give $\lambda_g = 285$ nm for TM$_0$ mode in the SOI slab waveguide. In case of 1D L/S grating, Eq. (5) is applied, and spatial patterns with two-fold symmetry can be observed as shown in Figs. 4(a) and (c) respectively for forward ($p > 285$ nm) and backward ($p < 285$ nm) waves. As the $p$ increases, the patterns move away from the center in case of the forward wave [Fig. 4(a)], and come close to the center in case of the backward wave [Fig. 4(c)]. As for the 2D hole array grating, both Eqs. (2) and (5) are applied, and spatial patterns with four-fold symmetry can be observed as shown in Figs. 4(b) and (d). The same behavior of the shift in the spatial pattern with respect to $p$ can also be observed.

4. Electromagnetic simulation and experimental results

In order to verify the theoretical estimation in the previous section, and to access the performance quantitatively, three-dimensional (3D) electromagnetic simulation by finite difference time domain (FDTD) method is performed. The periodic boundary condition based on constant-$k$ method [28] is applied to the periodic grating structure, and absorbing boundary with the perfectly matched layer (PML) [29] is assumed for top and bottom boundaries. The optical constants of Au and Ti are expressed by the Lorentz–Drude oscillator model [30], those for silicon are based on the single-pole Lorentz model [21], and silicon dioxide SiO$_2$ (gate oxide and BOX) is assumed to have a fixed relative permittivity $\varepsilon_r$ of 2.13. The quantum efficiency is calculated as a ratio of absorbed power in the SOI layer to the incident power assuming that all the photogenerated carriers contribute to the photocurrent.

Fig. 5 shows the spatial patterns of the quantum efficiency by FDTD simulation for the SP antenna of 1D L/S grating. The simulation reproduces the theoretical estimation in that the spatial pattern of the quantum efficiency shows two gentle arcs with two-fold symmetry, the pattern moves away from the center as $p$ increases when $p$ is larger than $\lambda_g\sim285$ nm (forward propagation in SOI), and comes close to the center as $p$ increases when $p$ is smaller than $\lambda_g$ (backward propagation). However, the peak angle $\theta$ where the efficiency becomes maximum is $\sim1^\circ$ larger and smaller than the theoretical estimation in cases of forward [Fig. 5(c), (d), (e)] and backward propagations [Fig. 5(a), (b)], respectively. This can be explained by the shortening of the $\lambda_g$ by $\sim2$ nm due to the finite thickness of the SiO$_2$ claddings (gate oxide and BOX) for the SOI slab waveguide. The peak quantum efficiency reaches almost 40% thanks to the lateral light propagation in the SOI PD, which is the important feature as an angle selective PD.

Fig. 6 shows the spatial patterns of the quantum efficiency by FDTD simulation for the SP antenna of 2D hole array grating. The simulation reproduces the theoretical pattern with four-fold symmetry, and the behavior of the peak angle $\theta$ with respect to $p$ is also the same except for the case with $p = 280$ nm [Fig. 6(b)], which actually shows the large quantum efficiency $\sim$14% at the center since the $\lambda_g$ is shortened close to $p = 280$ nm. This relatively large shortening is manifested by the shift of the peak angle $\theta\sim2^\circ$.
Fig. 5 Simulated spatial patterns with respect to the azimuth ($\phi$) and elevation angles ($\theta$) for 1D L/S grating, $t_{SOI} = 100$ nm, $\lambda = 685$ nm, and various $p$’s.

Fig. 6 Simulated spatial patterns with respect to the azimuth ($\phi$) and elevation angles ($\theta$) for 2D hole array grating, $t_{SOI} = 100$ nm, $\lambda = 685$ nm and various $p$’s.

Fig. 7 Measurement setup for the spatial patterns of the PD quantum efficiency. Incident angles $\phi$ and $\theta$ are varied by the rotational stage and the goniometer, respectively. The XY stage controls the light spot to be at the PD even if the incident angles are varied. The quantum efficiency is calculated based on the measured photocurrent and the pre-calibrated light intensity.

Fig. 8 Measured spatial pattern with respect to the azimuth ($\phi$) and elevation angles ($\theta$) for (a) 1D L/S and (b) 2D hole array gratings with $t_{SOI} = 100$ nm, $\lambda = 685$ nm and $p = 300$ nm. $V_C$, $V_G$ and $V_{SUB}$ are 1, 2 and 40 V, respectively.

The integrity of the structure and the optical properties of larger and smaller than the theoretical estimation in cases of forward [Fig. 6(c), (d), (e)] and backward propagations [Fig. 6(a)], respectively. The difference in the type of the grating on the SiO$_2$ cladding (gate oxide), 1D L/S or 2D hole array, seems to cause this difference in the $\lambda_g$ in the SOI slab waveguide. The square peak with a small quantum efficiency in Fig. 6(b) can be explained by the coupling between the second-order diffraction from the grating and the TM$_1$ mode ($\lambda_g$~467 nm) in the SOI slab waveguide. Generally, the quantum efficiency obtained by the 2D hole array grating is smaller than that by the 1D L/S grating probably due to the smaller diffraction efficiency.

Using the measurement setup depicted in Fig. 7, the quantum efficiency of the PD is measured, and its spatial patterns for 1D L/S and 2D hole array gratings are shown in Figs. 8(a) and (b), respectively. Although the $\theta$ and the $\phi$ are limited to 14° and 180°, respectively, the simulated spatial patterns are reproduced qualitatively, and the capability as an ASP is verified.

The peak quantum efficiencies are 8.1% and 0.28% for 1D L/S and 2D hole array gratings, respectively, and are considerably smaller than 42% and 12% predicted by the FDTD simulation. This is mainly due to the unexpected presence of the fixed oxide and/or interface trapped charges in the gate oxide and the BOX, which make it difficult to maximize the quantum efficiency by the adjustment of $V_G$ and $V_{SUB}$ with reverse polarity [21]. Without the presence of such charges, we could routinely obtained the quantum efficiency of about 25% or more by the 1D L/S grating [21, 22, 24]. The integrity of the structure and the optical properties of
the material also need to be improved to realize the values predicted by the simulation.

As for the peak angle $\theta$ where the efficiency becomes maximum, the 1D L/S and 2D hole array gratings experimentally give $6.0^\circ$ and $8.6^\circ$, respectively, while the theory predicts $6.7^\circ$ for both. The same explanation for the FDTD simulation, i.e. the shortening of the propagation wavelength $\lambda_g$ in the SOI due to the finite clad SiO$_2$ thickness may be applicable to the latter, but other experimental issues such as the adjustment of the tilt and rotational angle offsets, which are included in the PD chip attachment to the measurement system, need to be taken into consideration.

It should be noted that the peak angles $\theta$ and $\phi$ are determined only by the $\lambda$, $\lambda_g$, and $\rho$, and not affected by the properties of the grating metals [22]. This should be beneficial for the accurate angle detection without being affected by the material processing.

5. Conclusion

An SOI PD with Au SP antenna was proposed to detect the light incident angles, and its characteristics were investigated by theory, FDTD simulation and experiment. Spatial patterns of quantum efficiency with respect to azimuth and elevation angles were analyzed for two different types of SP antenna with 1D L/S and 2D hole array gratings, and were found to show two-fold and four-fold symmetry, respectively. The angles corresponding to the peak quantum efficiency can be predicted theoretically by phase matching condition between the diffracted light from the grating and the propagation mode in the SOI slab waveguide, and can be controlled by the period of the grating. The theoretical prediction was successfully verified by the FDTD simulation and experiment with slight modification in the propagation wavelength $\lambda_g$ in the SOI due to the finite thickness of the cladding SiO$_2$. Considering the tightly-controlled angular selectivity, decent quantum efficiency and good manufacturability, it can be concluded that the proposed SOI PD is useful as an ASP for advanced imaging applications such as post-capture refocus, DOF extension, range finding, lensless imaging, etc.

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