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Extraordinary Incident Angle Dependence of External Quantum Efficiency in SOI Photodiode with Silver Line-and-Space Grating

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1. Introduction

The silicon-on-insulator (SOI) photodiode (PD) with an integrated metal grating has a unique spectroscopic characteristics, in that the quantum efficiency (QE) can be enhanced nearly one order of magnitude, and the peak wavelength can be tailored only by changing the grating period [1, 2]. This feature has been explained based on the coupling between the diffracted light and the propagation modes in the silicon slab waveguide, in which the lateral p-n junction PD is fabricated [2, 3]. In this paper, incident angle dependence of the PD is reported. An extraordinary peak split in the spectroscopic characteristics was found for a particular tilt direction, and the mechanism was analyzed considering the different contribution of forward and backward waves in the SOI PD.

2. Device Structure

Figure 1 shows (a) the device structure of the SOI metal-oxide-semiconductor (MOS) p-n junction PD with silver (Ag) line-and-space (L/S) grating and the incident light conditions, such as incident angles and polarization direction, and (b) the top view of a fabricated device. In this paper, two kinds of incident angle are defined. φ is the tilt from z axis to y axis parallel to the lines in the grating, and θ is the tilt from z axis to x axis perpendicular to the lines in the grating. PDs with the grating period p from 260 to 340 nm are fabricated. For normal TM-polarized light incidence, the PD with grating period p = 300 nm shows the external QE of 23 % at the wavelength of 705 nm. In the case without Ag L/S grating, the external QE is 2.7 % in the same illumination condition. Thus, the enhancement factor by the grating becomes as high as 8.5.

3. Results and Discussions

Figures 2 and 3 show the measured spectroscopic external QEs for different φ and θ, respectively, with TM-polarized light and Ag L/S grating period p = 300 nm. The spectroscopic external QE in Fig. 2 is almost unchanged even if φ is changed. As mentioned above, the external QE can be enhanced due to the efficient coupling between the diffracted light from the Ag L/S grating and the lateral SOI waveguide mode [2]. Since the lateral intensity period and phase of the diffracted light is almost unchanged by φ, the spectroscopic external QE does not depend on the φ variation. On the other hand, in the spectroscopic external QE with θ variation as shown in Fig. 3, the peak at the wavelength of 705 nm with θ = 0 (normal incidence) splits into two peaks for the tilt angles of θ = 10 and 20 deg. The similar behavior can be seen in the peak at the wavelength of 485 nm. As θ becomes larger, the wavelength shifts on both sides of the central peaks become larger. In order to explain the phenomenon, Fig. 4 illustrates the phase matching conditions for efficient coupling i.e. higher external QEs. Because the lateral wavelengths of diffracted lights sensed by the forward and backward waves in the SOI waveguide are different, the phase matching conditions are also different. Furthermore, the comparison between the dispersion relationship of 100-nm-thick SOI waveguide [3] and the experimental peak wavelengths as functions of $1/\{(1/p) \pm (1/\lambda)\sin\theta\}$, where λ is incident wavelength, is made in Fig. 5. These relationships coincide well, indicating that the diffracted lights can be phase-matched separately with the forward and backward waves in the SOI waveguide and efficiently absorbed at different wavelengths.

4. Conclusions

The incident angle dependence of the SOI-MOS p-n junction PD with Ag L/S grating was experimentally investigated. It was found that the peak in the spectroscopic external QE was split when the incident light is tilted in the plane perpendicular to the lines in the grating. This observation could be explained based on the phase difference in the diffracted lights from adjacent lines in the grating, leading to the different coupling conditions for forward and backward waves in the PD. This results indicates that the present PD can accurately detect the incident angle of the light in the wavelength domain, and applicable to a new type of spectrometer with integrated diffraction grating and sensitive photodetector.

Acknowledgement

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References

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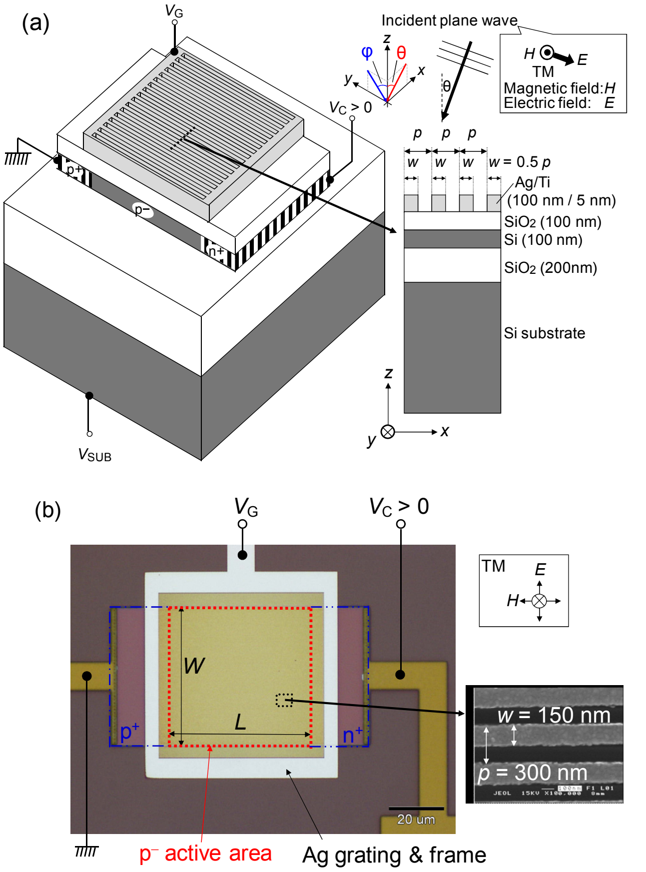

Fig. 1 (a) Devise structure of SOI-MOS p-n junction photodiode with Ag L/S grating and definitions of incident angles φ and θ, and incident polarization and (b) top view of a fabricated device. The light sensitive area equivalent to the p- active area is $L \times W = 50 \times 50\ \mu m^2$. As an adhesion layer, 5-nm-thick titanium (Ti) layer is inserted between the layers of SiO_2 and Ag. Since the L/S grating is surrounded by a frame, the grating can also work as a gate electrode for higher external QE by controlling the position of depletion region in SOI. The gate and the substrate biases are chosen at $V_G = -7$ V, and $V_{SUB} = 0$ V, respectively, for the highest external QE. The cathode voltage is fixed at $V_C = 1$ V.

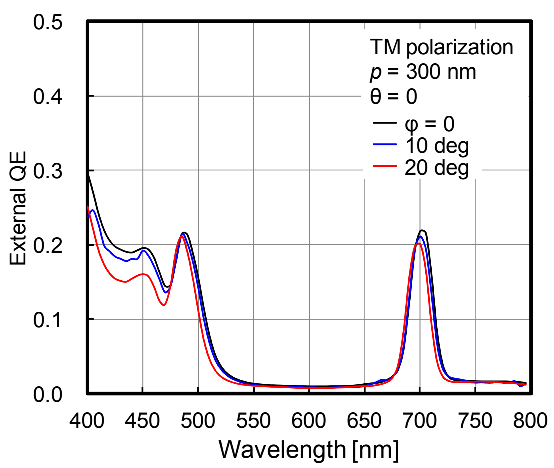

Fig. 2 Measured spectroscopic external quantum efficiencies (QEs) for different incident angle φ (θ = 0) with TM-polarized light and Ag L/S grating period $p = 300$ nm.

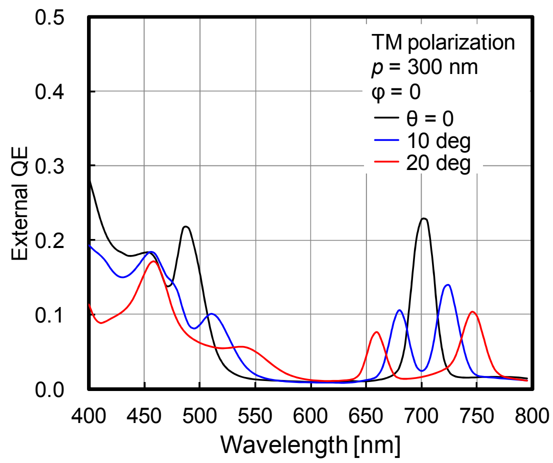

Fig. 3 Measured spectroscopic external quantum efficiencies (QEs) for different incident angle θ (φ = 0) with TM-polarized light and Ag L/S grating period $p = 300$ nm.

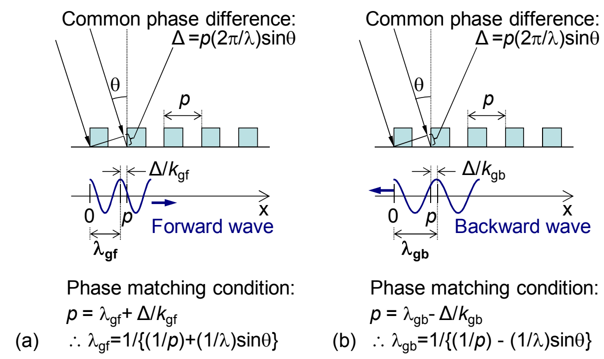

Fig. 4 Schematic diagrams of phase matching conditions between diffracted lights and (a) forward and (b) backward waves in the SOI waveguide. λ_{gf} and λ_{gb} are wavelengths of the forward and backward waves, respectively. $k_{gf} = 2\pi / \lambda_{gf}$ and $k_{gb} = 2\pi / \lambda_{gb}$ are wavenumbers for forward and backward waves, respectively.

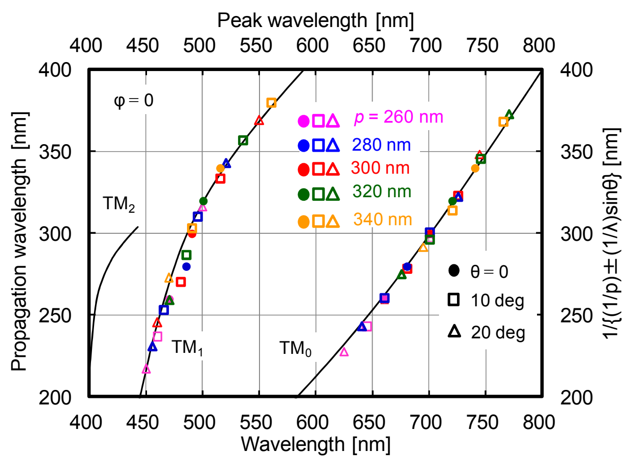

Fig. 5 Comparison between relationships of the calculated propagation wavelengths of the SOI waveguide modes vs. free-space wavelength (lower and left axes) [3], and the experimental peak wavelengths of the external QE vs. corresponding lateral wavelength of forward and backward waves (upper and right axes) for the case of θ variation (φ = 0).