Enhancement of SOI Photodiode Sensitivity by Aluminum Grating

Enhancement of SOI Photodiode Sensitivity by Aluminum Grating

Hiroshi Inokawa, Hiroaki Satoh, Ken Kawakubo, and Atsushi Ono

Research Institute of Electronics, Shizuoka University
3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan

Aluminum grating was applied to silicon-on-insulator (SOI) pn-junction photodiode to increase the light sensitivity. For 100-nm-thick diode, quantum efficiency (QE) of 26% (×15 enhancement) was attained at the wavelength of 700 nm. Wavelengths of the QE peaks for various grating pitches and light incident angles were examined, and it was confirmed that the coupling between the diffracted light from the grating and the propagation modes in the SOI slab waveguide caused the enhancement.

Introduction

Despite the popularity of silicon-on-insulator (SOI) for high-end integrated circuits, application to photodetectors is hampered due to the insufficient thickness for light absorption. In order to enhance the light absorption, use of the surface plasmon and other resonance modes in the noble metal (e.g. gold or silver) gratings has been proposed (1,2), and applied to metal-semiconductor-metal and Schottky photodiodes. We have proposed a different device structure (3) where the metal grating is isolated by the thick gate oxide from the top Si layer, which leads to the reduced junction leakage and the simple operation mechanism (i.e. coupling between the diffracted light and the propagation modes in the SOI slab waveguide), and allows the use of popular metals like aluminum (Al) as a grating material. In this paper, the characteristics of the SOI photodiode with Al grating are reported for various grating pitches and light incident angles, and the theoretical explanation for the operation mechanism is extended to the inclined light incidence.

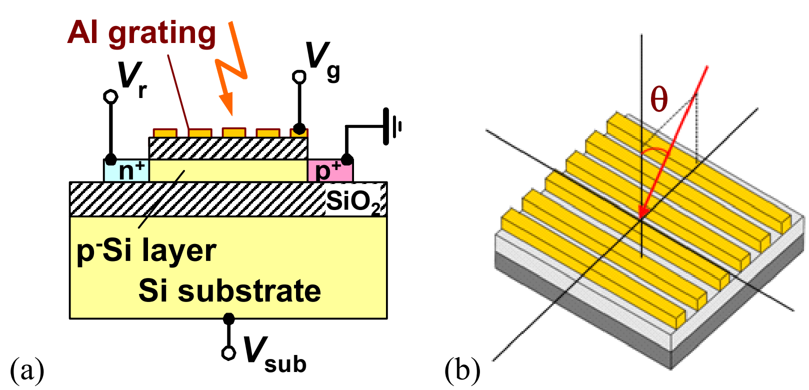

Figure 1. Structure of the SOI photodiode with line-and-space Al grating. (a) Cross-sectional view, and (b) bird's eye view.

Device Structure

Figure 1 shows the structure of the SOI lateral pn-junction photodiode with line-and-space Al grating. Thicknesses of Al grating, gate oxide, top Si layer and buried oxide are 110, 100, 100 and 200 nm, respectively. Dopant boron concentration in the top Si layer is less than 10^{15} cm^{-3}, and the p^{-} area is 50 × 50 μm^2. The grating pitch is varied from 260 to 340 nm, while keeping the duty ratio (line width / pitch) constant at 0.5. The grating is used not only for light diffraction, but also as a gate electrode to control the potential profile in the Si layer, and to maximize the depletion area. A monochromatic light with TM polarization (i.e. magnetic field parallel to the grating line) is shed to the photodiode, and the external quantum efficiency is calculated without any correction.

Results and Discussion

Figure 2 shows the spectroscopic QE of the fabricated photodiodes with various grating pitches *p*. We can see two peaks at around the wavelengths of 490 and 700 nm, whose

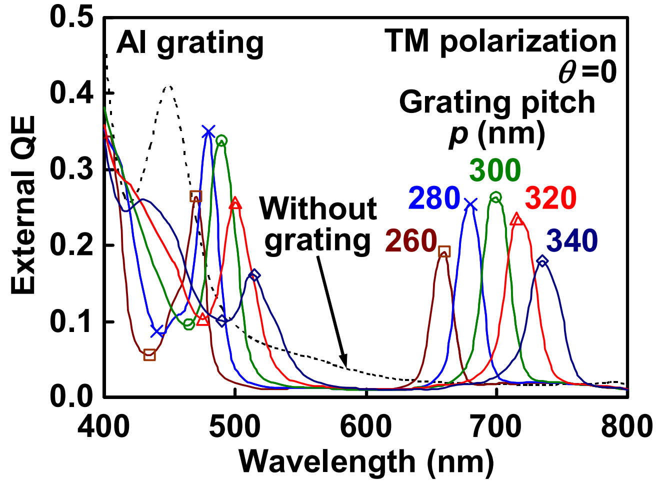

Figure 2. Spectroscopic quantum efficiency (QE) for various pitches *p* of the grating.

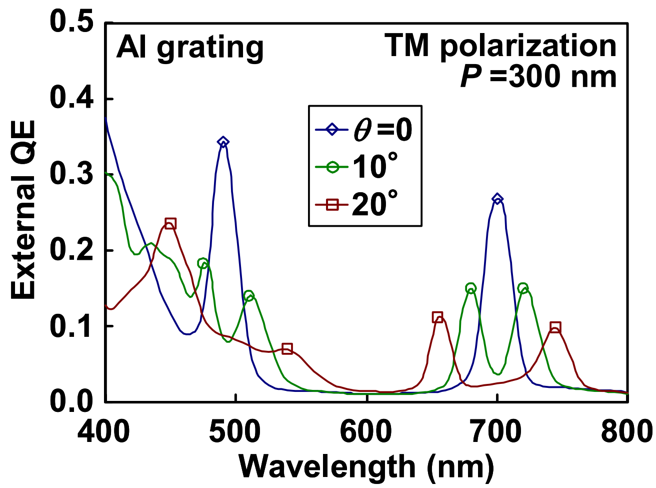

Figure 3. Spectroscopic quantum efficiency (QE) for various incident angles θ.

peak position can be tailored by changing the grating pitch *p*. Peak QEs for *p*=300 nm, for example, are 34 and 26% at 490 and 700 nm, respectively, which are 2.9 and 15 times larger than those without grating.

Figure 3 shows the QE spectra for different incident angles θ. Interestingly, the peaks split, and the separation becomes larger as the θ increases. The peak splitting is observed only when the incident light is tilted perpendicular to the grating line as shown in Figure 1(b) , and is not observed when titled parallel to the line.

This phenomenon can be explained based on the phase matching between the diffracted light and the propagating waves in the SOI waveguide as shown in Figure 4. When the incident light is tilted, phase difference Δ arises between the lights entering the adjacent lines in the grating. Specifically,

$$\Delta = p\,(2\pi/\lambda)\,\sin\theta. \quad [1]$$

Due to this phase difference, phase matching conditions for forward and backward waves in the SOI waveguide become different. That is, the propagation wavelength for the forward wave is

$$\lambda_{gf} = 1/\{(1/p) + (1/\lambda)\sin\theta\}, \quad [2]$$

and that for the backward wave is

$$\lambda_{gb} = 1/\{(1/p) - (1/\lambda)\sin\theta\}. \quad [3]$$

Then, equation [2] can be applied to the shorter wavelength of the split peak to give λ_{gf}, and equation [3] to the longer wavelength of the split peak to give λ_{gb}.

Figure 5 compares the theoretical dispersion curves (solid lines) for the waveguide modes in the Si slab sandwiched between infinitely thick SiO_2 layers (4), and those

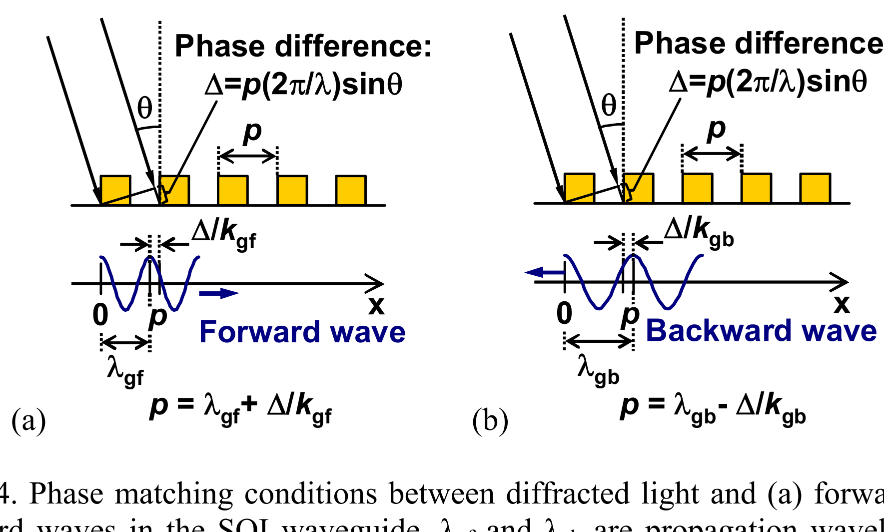

Figure 4. Phase matching conditions between diffracted light and (a) forward and (b) backward waves in the SOI waveguide. λ_{gf} and λ_{gb} are propagation wavelengths for forward and backward waves, respectively, and $k_{gf} = 2\pi / \lambda_{gf}$ and $k_{gb} = 2\pi / \lambda_{gb}$ are wavenumbers for forward and backward waves, respectively.

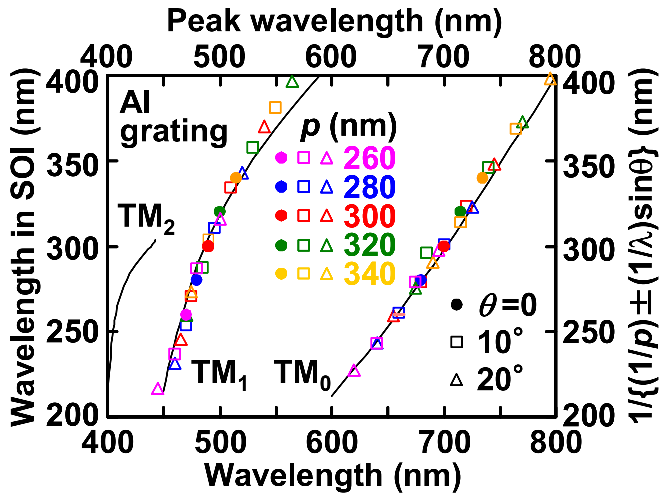

Figure 5. Theoretical (solid line) and experimental (symbols) dispersion curves for the propagation modes in the SOI slab waveguide sandwiched by SiO_2.

obtained experimentally (symbols) using equations [2] and [3]. These coincide well indicating the validity of the above discussion, and the simplicity of the operation mechanism. Since the peak wavelengths are determined only by the grating pitch and the dispersion relationship of the Si slab waveguide, they are not affected by the grating material or geometries, i.e. grating thickness, width, etc.

Conclusion

Al grating was applied to SOI pn-junction photodiode to increase the light sensitivity. For 100-nm-thick diode, QE of 26% (×15 enhancement) was attained at the wavelength of 700 nm. Wavelengths of the QE peaks for various grating pitches and light incident angles were examined, and it was found that the QE peaks could be controlled by the grating pitch, and the peak split when the incident light was tilted. The theoretical analysis successfully explained the behavior of the peak wavelengths, indicating that the coupling between the diffracted light from the grating and the propagation modes in the SOI slab waveguide caused the enhancement. The Al grating is sure to open up new opportunities for SOI-based photodetectors.

Acknowledgments

Authors are indebted to the Solid State Division of Hamamatsu Photonics K.K. for providing the SOI photodiodes before fabrication of the metal gratings.

References

1. T. Ishi, J. Fujikata, K. Makita, T. Baba, and K. Ohashi, *Jpn. J. Appl. Phys.*, **44,** L364 (2005).
2. D. Crouse and P. Keshavareddy, *J. Opt. A* **8**, 175 (2006).
3. H. Satoh, A. Ono, and H. Inokawa, *IEEE Trans. Electron Devices*, **60**, 812 (2013).
4. J. M. Liu, *Photonic Devices*, p. 95, Cambridge Univ. Press, Cambridge (2005).