Enhancement of SOI Photodiode Sensitivity by Aluminum Grating

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Despite the popularity of SOI for high-end integrated circuits, application to photodetectors are 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. Our approach [3] is unique in that the metal grating is isolated by the thick (~100 nm) gate oxide from the top Si layer (Fig. 1), which results in simple operation (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).

Fig. 2 shows the spectroscopic quantum efficiency (QE) of the proposed photodiodes with various grating pitches p. We can see two peaks at around the wavelengths of 490 and 700 nm, whose 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.

Fig. 3 shows the QE spectra for different incident angles θ. Interestingly, the peaks split, and the separation becomes larger as the θ increases. 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, eq. (2) can be applied to the shorter wavelength of the split peak to give λ_{gf}, and eq. (3) to the longer wavelength of the split peak to give λ_{gb}.

Fig. 4 compares theoretical dispersion curves [4] (solid lines) and those obtained experimentally (symbols) using eqs. (2) and (3). These coincide well indicating the validity of the above discussion, and the simplicity of the operation. Since the peak wavelengths are determined only by the grating pitch and the dispersion relationship of the SOI waveguide, they are not affected by the grating material or geometries, i.e. grating thickness, width, etc.

In summary, 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 suggested that the coupling between the diffracted light from the grating and the propagation modes in the SOI slab waveguide caused the enhancement.

[1] T. Ishi, et al., Jpn. J. Appl. Phys. **44** (2005) L364.
[2] D. Crouse and P. Keshavareddy, J. Opt. A **8** (2006) 175.
[3] H. Satoh, et al., IEEE Silicon Nanoelectronics Workshop, p. 33 (2011).
[4] J. M. Liu, *Photonic Devices*, Cambridge Univ. Press (2005).

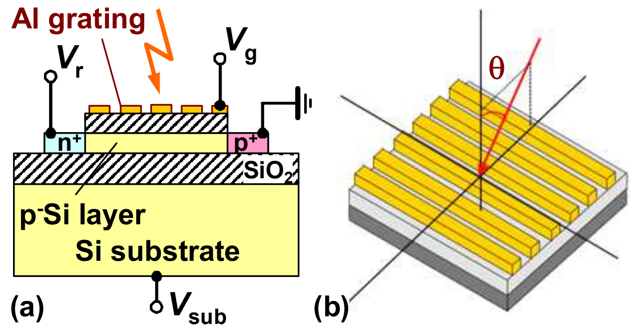

Fig. 1 Structure of the SOI photodiode with line-and-space grating. (a) Cross-sectional view, and (b) bird's eye view.

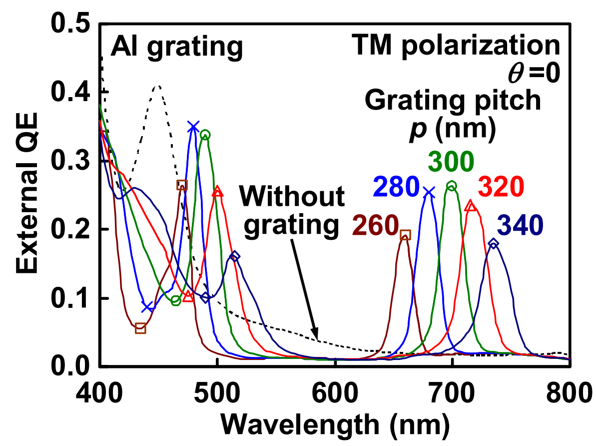

Fig. 2 Spectroscopic quantum efficiency (QE) for various pitches p of the grating. Thicknesses of the gate oxide, top Si layer and BOX are 100, 100 and 200 nm, respectively. TM implies the magnetic field parallel to the grating.

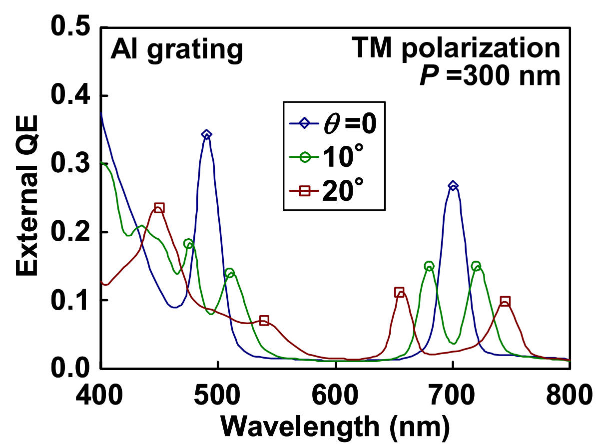

Fig. 3 Spectroscopic quantum efficiency (QE) for various incident angles θ.

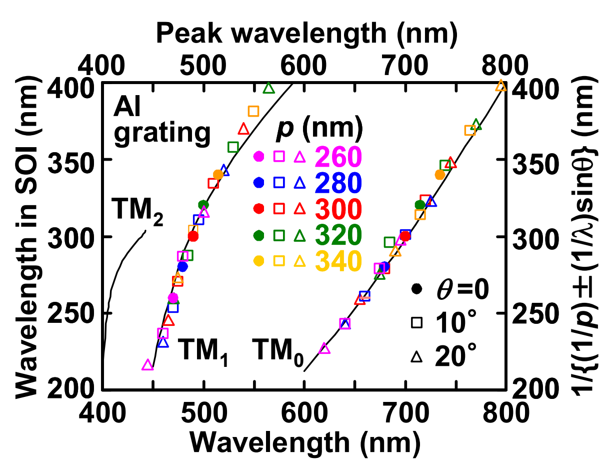

Fig. 4 Theoretical (solid line) and experimental (symbols) dispersion curves for the propagation modes in the SOI slab waveguide sandwiched by SiO_2.