Design and simulation of blue/violet sensitive photodetectors in silicon-on-insulator*

Han Zhitao(韩志涛)[1,2], Chu Jinkui(褚金奎)[1,2,†], Meng Fantao(孟凡涛)[1,2], and Jin Rencheng(金仁成)[1,2]

(1 Key Laboratory for Micro/Nano Technology and System of Liaoning Province, Dalian University of Technology, Dalian 116024, China)
(2 Key Laboratory for Microsystem and Microfabrication of the Education Department of Liaoning Province, Dalian University of Technology, Dalian 116024, China)

Abstract: According to Lambert's law, a novel structure of photodetectors, namely photodetectors in silicon-on-insulator, is proposed. By choosing a certain thickness value for the SOI layer, the photodetector can absorb blue/violet light effectively and affect the responsivity of the long wavelength in the visible and near-infrared region, making a blue/violet filter unnecessary. The material of the SOI layer is high-resistivity floating-zone silicon which can cause the neutral N type SOI layer to become fully depleted after doping with a P type impurity. This can improve the collection efficiency of short-wavelength photogenerated carriers. The device structure was optimized through numerical simulation, and the results show that the photodiode is a kind of high performance photodetector in the blue/violet region.

Key words: photodetectors; silicon-on-insulator; quantum efficiency; resonant cavity enhancement
DOI: 10.1088/1674-4926/30/10/104008 **PACC:** 0670D; 2940P **EEACC:** 7230C

1. Introduction

Silicon photodetectors have many advantages such as small volume, low noise, quick response and high sensitivity. In particular, they have good compatibility with microelectronic devices, and thus have been extensively applied in civil and military areas[1]. Conventional silicon photodetectors use bulk silicon wafer as the substrate material. Those devices have a wide spectral response range (400–1100 nm), and their peak response wavelength is about 800–900 nm. As the quantum efficiency (QE) of blue/violet light is very low, a great deal of work has been done to improve it[2].

Our research team plans to take advantage of polarized light in the sky to realize the robot's orientation and navigation[3]. Preliminary measurements of the polarized light in the sky have been carried out and the results show that the polarization information is stronger in the blue/violet region compared with that in the visible and near-infrared regions. In addition, the polarization information in the long-wavelength region is susceptible to the environment, so the blue/violet region is the ideal information source. In the polarized light sensor model, we combine silicon photodiodes with a blue/violet filter. However, this increases the fabrication cost. It also increases the system complexity and assembly difficulty. In order to restrain the responsivity of longer wavelengths, Ochi[4] took an epitaxy wafer as a substrate material, limiting light absorption in the epitaxy layer. However, the cost of the epitaxy wafer is high and the fabrication process is complicated. Purica[5] adopted the back-etching method to reduce the thickness of the bulk wafer. But it is difficult to achieve uniformity in the device layer and reproducibility of the process is poor.

With the fast development of the semiconductor industry, the cost of SOI wafers is continuously declining. SOI-based devices are attracting more interest from researchers. According to the requirement of bionic micro/nano navigation sensors, we propose and design a novel photodetector based on SOI substrate. The photodetector improves the QE of short wavelengths while limiting the responsivity of longer wavelengths to a very low degree by making use of the isolation function of the middle buried oxide (BOX) layer. Therefore, use of a blue/violet filter becomes unnecessary in the new sensor.

2. Structural design of the device

Figure 1 shows the structure of the silicon photodiode designed by the authors. The substrate material is back-etched silicon-on-insulator (BESOI) with a (phosphorus-doped) N type SOI layer, with a <100> orientation, floating zone (FZ) monocrystalline silicon, 2000–4000 Ω·cm in resistivity and 2 ± 0.5 μm in thickness. The thickness of the BOX is 0.5 μm. The handle wafer is N type, 525 ± 15 μm in thickness. The PN junction was formed by boron fluoride (BF_2^+) ion implantation through a thin silicon dioxide layer. In order to reduce the contact resistance, N type heavy doping was carried out in the N type electrode area. The metallurgical material Ti/Al was sputtered on the upper surface in order to form the anode and cathode. A certain thickness of silicon dioxide on the active area serves as a passivation and protection layer.

2.1. Theoretical analysis

According to Lambert's law, the power of the monochromatic light which is perpendicularly incident on the active area decays exponentially.

* Project supported by the State Key Development Program for Basic Research of China (No. 2006CB300407).
† Corresponding author. Email: chujk@dlut.edu.cn
Received 8 April 2009, revised manuscript received 12 May 2009

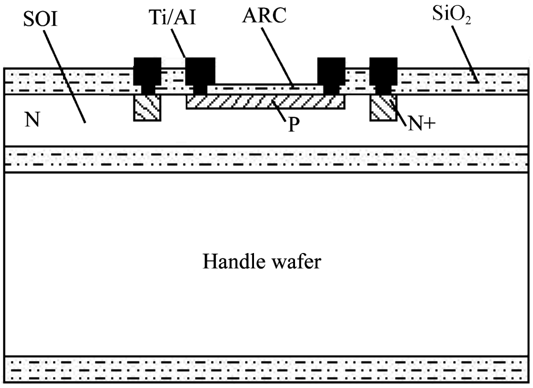

Fig. 1. Structural schematic of the photodiode based on SOI.

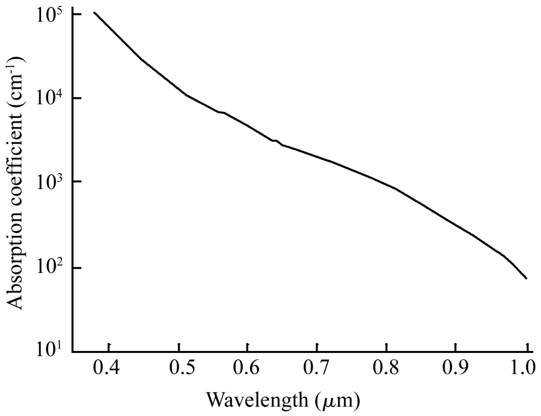

Fig. 2. Absorption coefficient of silicon material versus wavelength.

$$\Phi(x) = \Phi_0 e^{-\alpha x}. \tag{1}$$

The generation rate of photogenerated carriers is $G(x)$.

$$G(x) = -\frac{d\Phi(x)}{dx} = \alpha \Phi_0 e^{-\alpha x}, \tag{2}$$

where x denotes the depth which photon travels in silicon; Φ_0 denotes the incident optical power at $x = 0$; α denotes the absorption coefficient of the silicon material which varies with incident wavelength as shown in Fig. 2.

Figure 2 shows that the absorption coefficient of short wavelengths is so high that the penetration depth (the depth corresponding to absorption of 63.2% incident light) of the 450 nm wavelength is about 250 nm. In contrast, the absorption coefficient of long wavelengths is very low and the penetration depth of the 850 nm wavelength is about 20 μm. Owing to the thick device layer of the bulk wafer, long-wavelength photons can be absorbed efficiently, so the QE of long wavelengths is high. Blue/violet light will be absorbed in a very thin layer near the active area where many more defects resulting from contamination and implantation damage exist. These defects reduce the carrier lifetime sharply, resulting in a very short carrier diffusion length. Thus the carriers are easily lost due to recombination in the defects. This is the reason why the QE of short-wavelength light is low.

The BOX layer of the SOI wafer can isolate the device layer from the handle wafer effectively. The thin device layer absorbs only a few of the incident photons in the visible and near-infrared regions. Most of the photons of long-wavelength light penetrate through the BOX layer and are absorbed in the handle wafer. Due to the isolation function, the photodetecor can realize the constraints of responsivity of long wavelengths. Therefore, by choosing an appropriate thickness value for the device layer, the photodetecor can achieve high QE in the short-wavelength region and low QE in the long-wavelength region at the same time.

The lifetime of the minority is one of the most important parameters which can be used to characterize the crystalline integrity and the doping. It is in an inverse ratio with dark current. High-quality, high-resistivity silicon wafers can offer longer minority carrier lifetimes, which is favorable for reducing dark current. Compared with the Czochralski (CZ) wafer, the floating-zone (FZ) wafer usually offers very high resistance, and we therefore choose an FZ wafer as the device layer material. We suppose that the dopant concentration of the N type substrate and P type layer are 1.5×10^{12} and 1×10^{17} cm^{-3} respectively. The PN junction is quite abrupt and the PN junction depth is about 0.5 μm. According to Eq. (3), the calculated built-in potential voltage is 0.537 V.

$$V_{bi} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}, \tag{3}$$

where k is Boltzmann's constant; n_i denotes the intrinsic carrier concentration, whose value is about 9.65×10^9 cm^{-3}. The space charge region (SCR) is mainly depleted on the lightly doped side. According to Eq. (4), the calculated SCR in the N region is 26.36 μm which is much larger than the thickness of the N type layer. So the N type layer can be completely depleted under the built-in electrical field without any external reverse bias.

$$W = \left\{ \frac{2\varepsilon_s V_{bi}}{q} \left[\frac{N_a}{N_d}\right] \left[\frac{1}{N_a + N_d}\right] \right\}^{1/2}, \tag{4}$$

where ε_s denotes the permittivity constant of silicon. The operational principle of photodetectors mainly depends on the depleted layer to separate the photogenerated electron-hole pair. The electrons and holes are then moved to the N and P regions respectively. A fully depleted N type layer is therefore favorable to improve the QE of short-wavelength light.

2.2. Optimized design of the thickness of the surface silicon dioxide

Surface reflection of the active area is of great importance to photodetector external QE. The reflectivity in the blue/violet spectrum is very high on a naked silicon surface, so it is necessary to fabricate an anti-reflection coating (ARC) whose material is usually silicon dioxide or silicon nitride or both. The preparation of SiO_2 is simple and it has a good passivation effect. So we choose SiO_2 as the ARC to simulate and analyze the performance of the photodiode. The reflectivity can be calculated as follows[7]:

$$R = |r|^2, \tag{5}$$

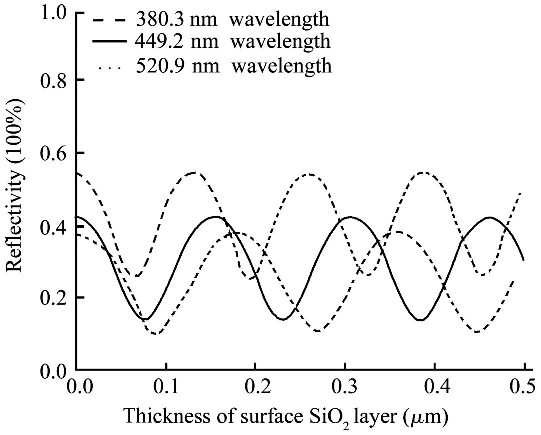

Fig. 3. Surface reflectivity versus silicon dioxide layer thickness.

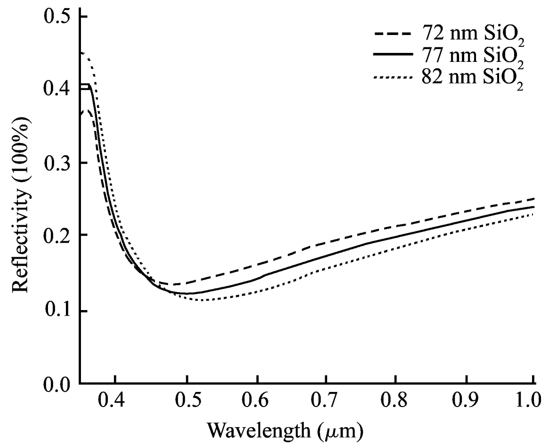

Fig. 4. Surface reflectivity versus wavelength.

$$r = \frac{r_{01} + r_{12}e^{i\delta}}{1 + r_{01}r_{12}e^{i\delta}}. \tag{6}$$

r denotes the complex reflectivity under the perpendicularly incident condition. r_{01}, r_{12}, δ can be calculated as follows:

$$r_{01} = \frac{n_0 - n_1}{n_0 + n_1}, \tag{7}$$

$$r_{12} = \frac{n_1 - n_2 - ik_2}{n_1 + n_2 + ik_2}, \tag{8}$$

$$\delta = \frac{4\pi d}{\lambda} n_1. \tag{9}$$

n_0, n_1, n_2 represent the reflectivity of air, silicon dioxide and silicon respectively. k_2 denotes the extinction coefficient of silicon material. λ represents the incident wavelength.

The device's reflectivity in the 380–520 nm range is the target to be optimized and 450 nm is selected as the central wavelength. Figure 3 shows that the reflectivity of the 380.3, 449.2 and 520.9 nm wavelengths changes periodically as the thickness of the silicon oxide increases. Their first troughs are comparatively centralized, which indicates that this oxide thickness range is ideal for short-wavelength light. It can be seen from Fig. 3 that the reflectivity of the 449.2 nm wavelength is minimal when the silicon oxide thickness is 77 nm. Meanwhile, the reflectivity of 380.3, 449.2, 520.9 nm is 29.8%, 13.9%, 12.6% respectively.

Some fabrication error will occur when using the oxidation method of dry oxygen to fabricate the silicon oxide on the active area. The error range is about ±5 nm. Figure 4 shows that the reflectivity varies with incident wavelength. From Fig. 4, it can be seen that when the oxide is thinner, the reflectivity in the short-wavelength region is lower, whereas the reflectivity in the longer-wavelength region increases. This is favorable to improve the QE of the blue light. So the thickness of oxide should be less than 77 nm.

2.3. Analysis of the resonant cavity enhancement effect

The incident light will be partially reflected at the interface between the SOI and BOX layers due to the difference in refractivity. Thus, in an SOI-based photodetector structure, the surface oxide at the active area, the SOI layer and the BOX layer form a resonant cavity enhancement (RCE) structure. The existence of the RCE structure influences the responsivity at certain wavelengths. Using Eq. (10) in Ref. [8], we analyze the RCE effect on photodiode performance. f_{RCE} is defined as the RCE factor, as shown in Eq. (11).

$$\eta = \left(1 - e^{-\alpha d}\right)(1 - R_1) f_{\mathrm{RCE}}, \tag{10}$$

$$f_{\mathrm{RCE}} = \frac{1 + R_2 e^{-\alpha d}}{1 - \beta + R_1 R_2 e^{-2\alpha d}}, \tag{11}$$

$$\beta = 2\sqrt{R_1 R_2} e^{-\alpha d} \cos\left(\frac{4n\pi d}{\lambda} + \psi_1 + \psi_2\right). \tag{12}$$

R_1 denotes the reflectivity at the interface between the surface oxide and air; R_2 denotes the reflectivity at the interface between the SOI and BOX layers; d denotes the thickness of the SOI layer.

If the monochromatic light is normally incident on the active area, $\psi_1 = \psi_2 = 0$. Figure 5 shows that f_{RCE} varies with wavelength when the thickness of the SOI layer is 1.5, 2.0 and 2.5 μm. As shown in Fig. 5, the RCE effect is negligible in the short-wavelength region which reveals that short-wavelength light is absorbed completely in the SOI layer. In contrast, the RCE effect is clear and increases periodically in the long-wavelength range. Furthermore, the RCE effect increases as the SOI layer decreases. Because the RCE effect is disadvantageous for the responsivity restraint of long wavelengths, it is necessary to choose an appropriate thickness for the SOI layer. From Fig. 5, one can deduce that when the SOI layer is 2 μm, the RCE effect is negligible owing to the low responsivity of long-wavelength light.

3. Results and discussion

Hamamatsu is one of the best photodiode manufacturers in the world. The S1087-01 type photodiode they produce is made of bulk silicon which has a wide spectral response. The S1087 type photodiode, which adds a blue/violet filter to the S1087-01, restrains the wavelength responsivity more than 560 nm. We choose both of them to compare with our designed photodiode based on SOI. As shown in Fig. 6, it can be seen that our designed photodetector has a higher QE in the

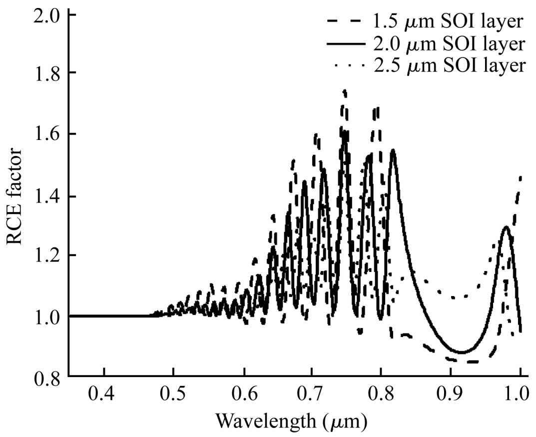

Fig. 5. RCE factor versus wavelength.

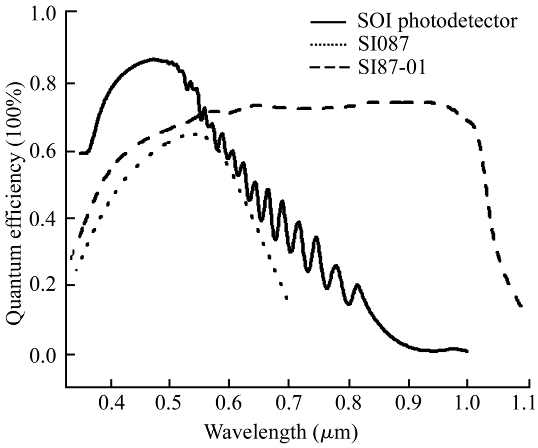

Fig. 6. Quantum efficiency versus wavelength.

short-wavelength range than either of them. Furthermore, our photodetector restrains the QE of longer wavelengths without any filter. The simulation results show that our designed photodetector is a high-performance photodiode.

4. Conclusion

According to the requirements of polarized light sensors，a novel photodetector in SOI was proposed. By choosing a proper thickness value for the SOI layer, this device can impress the responsivity of longer wavelengths in the visible and near-infrared regions, making a blue/violet filter unnecessary in the measurement of polarized light. High-resistivity floating-zone silicon makes the device layer become fully depleted, which improves the QE in blue/violet region effectively. The anti-reflection coating is optimized and simulation results show that the designed photodiode is a high-performance blue/violet sensitive photodetector which has great potential in optoelectronic integrated circuit (OEIC) and short distance fiber communication applications.

References

[1] Feng Xiaoqiang, Hou Xun, Yang Wenzheng, et al. Photoelectric detection of overprint deviation in color printing. Acta Photonica Sinica, 2003, 32(33): 1336 (in Chinese)

[2] Ning Baojun, Zhang Taiping, Zhang Lu, et al. Silicon PIN photodiode for UV and blue spectral regions. Chinese Journal of Semiconductors, 2002, 23(2): 174 (in Chinese)

[3] Chu Jinkui, Zhao Kaichun, Wang Tichang, et al. Research on a novel polarization sensor for navigation. IEEE Proceedings of the 2007 International Conference on Information Acquisition, 2007: 241

[4] Ouchi H, Mukai T, Kamei T, et al. Silicon pn junction photodiodes sensitive to ultraviolet radiation. IEEE Trans Electron Devices, 1979, 26(12): 1965

[5] Purica M, Budianu E, Elena M. Blue/ultraviolet sensitive detector on ⟨100⟩ silicon membrane. IEEE Semiconductor Conference, 2002, 1: 211

[6] Sze S M. Physics of semiconductor devices. 2nd ed. New York: Wiley, 1981

[7] Nestell Jr J E, Christy R W. Optics of thin metal films. American Journal of Physics, 1971, 39: 13

[8] Unlu M S, Strite S. Resonant cavity enhanced photonic devices. J Appl Phys, 1995, 78(2): 607