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Study on high signal-to-noise ratio (SNR) silicon *p-n* junction photodetector

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On the basis of *n*-type single-crystal (100) silicon substrate, a silicon *p-n* junction photodetector has been successfully developed. Three methods to improve photoresponse signal-to-noise ratio (SNR) were profoundly studied: the *p-n* junction depth was optimized to enhance the spectral responsivity within the wavelength range of 500–600 nm, an antireflection layer with the appropriate thickness was added to reduce the reflected light and enhance the sensitivity, the adjustment technique of spectral band response was adopted to remove the noise signal with normal silicon absorptive wavelengths. Eventually, the spectral responsivity SNR can be over 10^4 at 500–600 nm while the peak of spectral responsivity is 0.48 A/W at about 520 nm. After being optimized, silicon *p-n* junction photodetectors, which possess the properties of lower dark current, higher sensitivity, shorter response time and larger SNR, can be achieved.

Keywords: silicon *p-n* junction photodetector, antireflection layer, adjustment technique of spectrum band, spectral responsivity, high signal-to-noise ratio (SNR).

1. Introduction

Photodetector is an optical receiver which transforms the energy of optical radiation (such as infrared, visible light or ultraviolet) into the electrical signal that is convenient for measurements [1]. These detectors are extensively used in many domains, such as biology, medical treatment, communication, finance, aviation, *etc*. The development of semiconductor *p-n* junction photodetector is based both on the principle of internal photoelectric effect and on the theory of *p-n* junction [2]. Presently, most of the photodetectors, which include photoresistors, photodiodes, phototransistors integrated photodetectors and so on, belong to semiconductor photodetectors and mostly adopt the material of element semiconductor and compound semiconductor. The detection range of these photodetectors is from infrared to visible light [3], but some devices can even detect ultraviolet response [4]. Due to the different optical wavelength of the diverse fields, the special performance parameters are required. In the paper, the operational wavelength of this photodetector is 500–600 nm.

On a substrate of *n*-type single-crystal (100) silicon, the silicon *p-n* junction photodetector has been developed. After the detector's properties were measured

and analyzed, the spectral responsivity appeared to be sensitive within the range of the wavelength 400–1200 nm. Due to adopting single-crystal silicon material as substrate and the manufacture technology which is completely compatible with standard CMOS technology, the detector can be volume-produced at reduced costs, and the properties of the detectors are steady and reliable.

The spectral responsivity of photodetector is determined by its materia1. At the room temperature, since the bandgap of silicon is 1.12 eV, the peak value of the spectral responsivity of silicon photodetector is at about 950 nm. In the near infrared region, the optical absorption coefficient for silicon is small, which means that the majority of the incidents photons can penetrate through the surface and generate the carriers in the intrinsic region, thus the responsivity of the photodetector is high. While in the short wavelength region, *i.e.*, in the waveband from visible to ultraviolet light, the optical absorption coefficient is so great that the radiation is absorbed near the surface, so that the photogenerated carriers would be recombined before they are collected in the intrinsic region, then the responsivity decreases rapidly with decrease of the wavelength [5]. In order to improve the responsivity of silicon photodetector at the 500–600 nm, three methods of improving photoresponse signal-to-noise ratio (SNR) were emphatically studied. If the design parameters are adjusted appropriately, some high SNR photodetector can be obtained for blue region or near infrared region.

2. Design of the silicon *p-n* junction photodetector

The cross-section of the silicon *p-n* junction photodetector is shown in Fig. 1. Its operational principle includes three processes: the incident light generates photogenerated carrier; the transmission causing that carriers penetrate through the depletion region of *p-n* junction which produces current; the current act on exterior closed circuit and generate the output signal.

To obtain silicon *p-n* junction photodetectors possessing the properties of lower dark current, higher sensitivity, shorter response time and larger SNR, the design is optimized in order to achieve the following four goals.

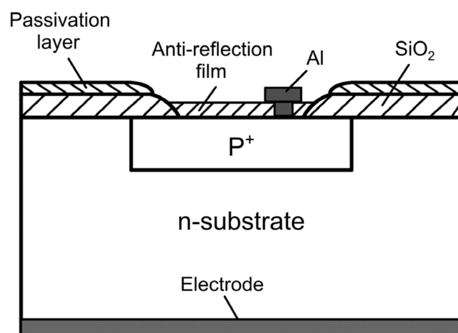

Fig. 1. Cross-section of silicon *p-n* junction photodetector.

2.1. To reduce dark current

The device demands low dark current. The dark current I_D is composed of the generation current I_G in barrier region and the diffusion current I_{diff} of the diffusion region. At the room temperature, for silicon, the generation current is greater than the diffusion current, $I_G \gg I_{\text{diff}}$ [3]. The diffusion current can be neglected, and the expression of dark current is [6]:

$$I_D \approx I_G = A_j \frac{q n_i}{2\tau_p} \left(\frac{2\varepsilon_r \varepsilon_0 V_D}{q N_D} \right)^{\frac{1}{2}} \tag{1}$$

where n_i is intrinsic carrier concentration of silicon, ε_r, ε_0 are the relative dielectric coefficient and vacuum dielectric coefficient, respectively, V_D is the applied voltage, N_D is the doping concentration of *n*-type substrate, τ_p is the minority carrier lifetime, q is the electron charge, A_j is the *p*-*n* junction area. Because q, ε_r, ε_0 and n_i are all constant and V_D is a fixed value, only τ_p, A_j, N_D can be changed. To reduce the dark current of the devices, the major methods lead to increasing of the τ_p, reducing of the junction area A_j, and introducing *n*-type substrate material with low resistivity. But the minority carrier lifetime will be shortened with the increasing of substrate doping concentration; the resistivity couldn't be too low.

2.2. To shorten response time

When the photodetector is under ray radiation, time lag exists before the generated signal reaches its steady-state. Once the radiation is halted, time lag also exits before signal vanishes completely. The phenomenon of time lag is called inertia which is expressed by response time. Response time is influenced by the time constant τ which is determined by detector and peripheral circuit. The equivalent circuit of photodetector is shown in Fig. 2. In the figure, I_S stands for photocurrent, R_S is the series resistance of photodiode, R_L is the load resistance, and C_D is junction capacitance. The response time of photodetector is expressed by:

$$\tau = RC = \left(R_S + R_L\right) C_D \tag{2}$$

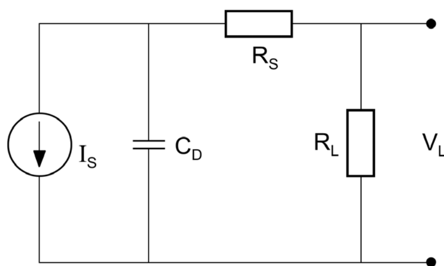

Fig. 2. Equivalent circuit of photodetector.

It seems that the major parameters which effect response time are the series resistance R_S and junction capacitance C_D. By increasing of substrate doping concentration N_D or reducing the junction area A_j it is possible to shorten the response time τ.

2.3. To improve sensitivity

The photocurrent expression for silicon *p*-*n* junction photodetector is computed by:

$$I_L = qGA_j\left(L_n + L_p + X_m\right) \tag{3}$$

where q is the electron charge, G is the generation rate of electron-hole pairs, A_j is the area of *p*-*n* junction, L_n and L_p are minority carrier diffusion lengths of *p* and *n* region, respectively, X_m is the barrier width of *p*-*n* junction. From Eq. (3), it can be concluded that the photocurrent is related to the selection of material (resistivity, lifetime of minority carrier, *etc.*), junction area A_j and the barrier width X_m. For the *p*-*n* junction photodetector, we should ensure not only that the given incident photons generate more photocarriers in the semiconductor, but also that the photocarriers can enter *p*-*n* junction and penetrate its depletion layer.

It is concluded that the middle-impedance *n*-type (100) single-crystal silicon with long lifetime can be adopted as substrate, while the junction depth of *p*-*n* junction is shallow and the junction area A_j is 17.5 mm^2.

2.4. To enhance SNR

The noise is one of the major influencing factors of the detection range. The SNR is usually used to evaluate the performance of a photodetector system:

$$\mathrm{SNR} = \frac{S}{N} \tag{4}$$

where S, N is signal power and noise power, respectively.

Since photodetector's fundamental function is that transforming the power of the incident light into the corresponding photocurrent, in terms of this requirement, SNR is computed by:

$$\mathrm{SNR} = \frac{I_L(\lambda = 500\text{–}600\ \mathrm{nm})}{I_L(\lambda = 900\ \mathrm{nm})} \tag{5}$$

The peak wavelength of Si photodetector is too large (about 900 nm), so it is difficult to enhance the sensitivity and SNR under the shorter wavelength. To overcome thin difficulty, we specially optimize the *p*-*n* junction depth and add antireflection layer. Furthermore, the adjustment technique of spectrum band response is introduced to ensure that the photocurrent I_L at 500–600 nm is much larger than that at 600–1200 nm.

3. Results and discussions

According to the foregoing scheme, shallow junction photodiode 2CU series (2CU stands for photodiode fabricated on the substrate of the *n*-type silicon) were manufactured using standard CMOS technology. Then the properties of these devices are tested and analyzed, and finally the approaches to enhance SNR are discussed. To satisfy the various requirements concerning wavelengths from the different domains, three methods of improving the photoresponse SNR were emphatically studied: the *p*-*n* junction depth (x_j) was optimized to enhance the spectral responsivity within the wavelength range of 500–600 nm; an antireflection layer with the appropriate thickness was added to reduce the reflected light and enhance the sensitivity; adjustment technique of spectral band response was adopted to removed the noise signal with normal silicon absorptive wavelengths. Eventually, the spectral responsivity SNR can be over 10^4 within the wavelength range of 500–600 nm and the peak of spectral responsivity is 0.48 A/W at about 520 nm.

3.1. Optimizing the *p*-*n* junction depth x_j

The $1/\alpha$ is penetration depth of light wavelength λ, where α is photoabsorption coefficient. For the devices whose junction depth is x_j, minimum wavelength producing photoelectric effect is $x_j = 1/\alpha$. The absorption coefficient α of silicon is about 4500–7000 cm^{-1} within the wavelength range of 500–600 nm, and consequently the junction depth x_j is between 1.4 and 2.2 μm. Because the penetration depth of short wavelength light is thin, the shallow junction is in favor of improving sensitivity. Considering other factors, the junction depth x_j is determined to be of 1.7–1.8 μm.

3.2. Determining the thickness of antireflection layer

Since only 70% of the incident light enters the silicon semiconductor, an antireflection layer or multi-antireflection layer, whose refractive index is appropriate and optical loss is very small, should be added to the sensitive surface.

In the design, a thick SiO_2 film is added as antireflection layer. The results show that this film can enhance sensitivity as well as improve the reliability of the devices. By a series of experiments, the thickness of the antireflection layer is determined.

The relationship between the relative responsivity ($I_L/I_{L\max}$) and the thickness of antireflection layer (SiO_2) of $2CU_{02}$ photodetectors under zero bias is showed in Fig. 3. It is obvious that the relative responsivity reaches its peak when the thickness of antireflection layer (SiO_2) is 1/2 of the wavelength λ.

3.3. Variation of spectral responsivity curve introducing adjustment technique of spectral band

The peak responsivity of Si photodetector is at about 900 nm, however, the detected wavelength range of this detector is 500–600 nm. Consequently, the spectral band adjustment technique is adopted to further improve SNR. The spectral band adjustment

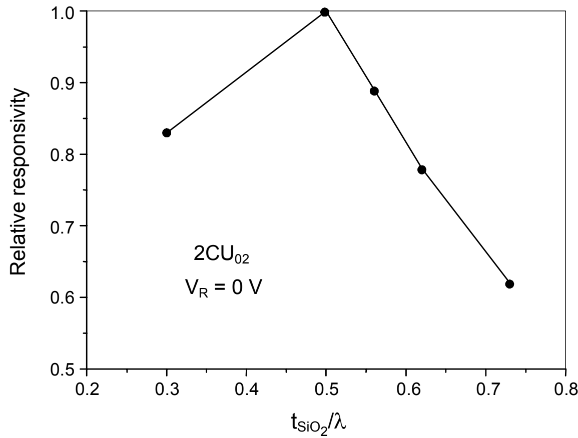

Fig. 3. Relationship between relative responsivity and thickness of antireflection layer.

technique is that a properly thin optical filter is presented to the detector by capsulation to improve SNR. Firstly, the optical glass is chosen, which has high transmissivity within wavelength range of 500–570 nm while low transmissivity within 650–1200 nm range. Secondly, to further reduce the transmissivity at 600–1200 nm, a reflective coating is added to the glass by coating technology, and thus the high SNR is achieved. This method can adjust the optional peak responsivity of the photodetectors, and these devices can meet all requirements of various systems.

3.3.1. Spectral responsivity curve without spectral band adjustment technique

With the monocolour radiation, the ratio of output current $I_{S\lambda}$ to the power of incident light $P_{S\lambda}$ is called spectral current responsivity

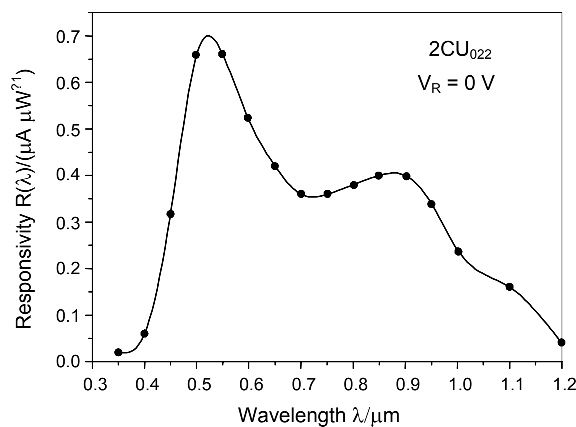

Fig. 4. Relationship between spectral responsivity $R(\lambda)$ and wavelength λ.

$$R_{I\lambda} = \frac{I_{S\lambda}}{P_{S\lambda}} \tag{6}$$

$R_{I\lambda}$ is different at various wavelengths. The relation curve between $R_{I\lambda}$ and λ is called spectral responsivity curve.

Without spectral band adjustment technique for $2CU_{02}$ photodetectors, spectral responsivity curve within 300–1200 nm range is tested, as shown in Fig. 4.

Figure 4 shows that the curve have two peak responsivity: one is 0.70 A/W at 520 nm, it is the response value of the detected wavelength; the other is 0.42 A/W at 900 nm, it is response value of the normal silicon absorptive wavelength. The latter is the noise needed to be removed. The SNR here is:

$$\mathrm{SNR} = \frac{I_L(\lambda = 500\text{–}600\ \mathrm{nm})}{I_L(\lambda = 900\ \mathrm{nm})} = \frac{0.70}{0.42} = 1.67 \tag{7}$$

3.3.2. Spectral responsivity curve with spectral band adjustment technique

After introducing the spectrum band adjustment for $2CU_{02}$ photodetectors, the responsivity curve within 300–1200 nm range is tested, as shown in Fig. 5. The figure shows that the only peak responsivity is 0.48 A/W at 520 nm. However, the photocurrent is nearly zero at the normal silicon absorptive wavelength (900 nm). The average SNR value is computed:

$$\mathrm{SNR} = \frac{I_L(\lambda = 500\text{–}600\ \mathrm{nm})}{I_L(\lambda = 900\ \mathrm{nm})} = 1.22 \times 10^4 \tag{8}$$

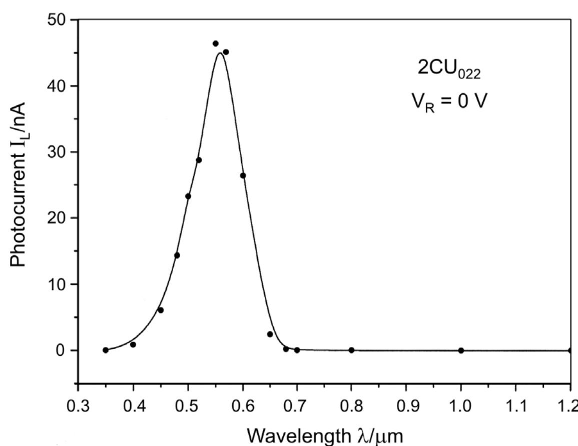

Fig. 5. Spectral responsivity of photodetector with filter.

To sum up the spectral band adjustment technique almost eliminates the noise and enhances SNR. The properties of these devices are greatly improved.

4. Conclusions

Adopting *n*-type (100) single-crystal silicon with middle-impedance and long lifetime as substrate, we successfully developed *p*-*n* junction photodetectors with low dark current, high sensitivity and great SNR. The average SNR of the photodetector can reach 10^4 at about 520 nm. In addition, according to the optimized design, high SNR photodetector for the specified wavelength range varying from blue spectral region to near infrared region can be easily obtained by adjusting properly *p*-*n* junction depth and thickness of antireflection layer and choosing the suitable performance of optical filter. Consequently, the application prospect for the detectors is cheerful.

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