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A study on temperature characteristics of green silicon photodetector

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Green silicon photodetector is successfully developed on the substrate of *n*-type single-crystal (100) silicon. To improve its performance, the detector is optimized by optimizing the *p*-*n* junction depth x_j and the thickness of antireflection layer to reduce dark current, shorten response time and increase sensitivity. The spectrum response 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. The temperature characteristics of the dark current at reverse bias and photocurrent at zero bias are emphatically investigated. Firstly, the temperature behavior of dark current at 10 V reverse bias voltage and temperature range of 253–323 K is studied. Results show that dark current is dominated by generation-recombination current I_{gr} the temperature range of 253–283 K and it is dominated by traps tunneling current I_{tt} at the temperature range of 283–323 K. Secondly, the temperature behavior of photocurrent at zero bias and temperature range of 213–353 K is discussed. Results show that photocurrent increases as temperature increases below room temperature and almost holds the line over room temperature. Consequently, photodetector fulfils quality requirements.

Keywords: green silicon photodetector, temperature characteristics, dark current, generation-recombination current, traps tunneling current.

1. Introduction

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 [1]. Presently, most of the photodetectors belong to semiconductor photodetectors and the materials of element semiconductor and compound semiconductor are mostly adopted. The detection range of these photodetectors is from infrared to ultraviolet. Due to the different optical wavelength of the diverse fields, the special performance parameters are required. In the paper, the operational wavelength of the photodetector is about 500–600 nm.

Green photodetector is developed on the substrate of *n*-type single-crystal (100) silicon. The spectral responsivity of photodetector is determined by the material. At room temperature, since the bandgap of silicon is 1.12 eV, the peak value of the spectral responsivity of silicon photodetector is about 950 nm. The spectral response of the detector is sensitive within the wavelength range 400–1200 nm. In order to improve the responsivity of silicon photodetector at 500–600 nm, three methods of improving photoresponse signal-to-noise ratio (SNR) were studied. If the design parameters are adjusted appropriately, some high SNR photodetector can be obtained for blue region or near infrared region.

Since silicon green photodetector is fabricated using semiconductor materials, its properties change with temperature. The photodetector works over the temperature range of 263–323 K. The temperature characteristics of the dark current and photocurrent at zero bias are investigated. Their results show that the photodetector operates well under the normal operating conditions.

2. Design of the silicon green photodetector

A schematic of the green photodetector is given in Fig. 1.

To reach high performance (such as lower dark current, higher sensitivity, shorter response time and so on), the detector is optimized in the following five aspects.

2.1. Reducing dark current

The device demands low dark current. The diffusion current can be neglected, and the expression of dark current I_D is [2]:

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

where n_i is the 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,

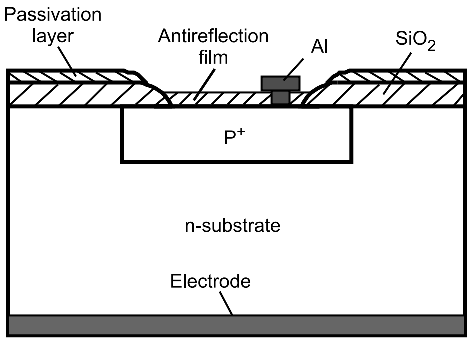

Fig. 1. Cross-section of silicon *p*-*n* junction photodetector.

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 are: increasing the τ_p, reducing the junction area A_j, and introducing *n*-type substrate material with low resistivity. But the minority carrier lifetime will be shortened as the substrate doping concentration increases; the resistivity cannot be too low.

2.2. Shortening response time

Response time is influenced by the time constant τ which is determined by the detector and peripheral circuit. The equivalent circuit of photodetector is shown in Fig. 2.

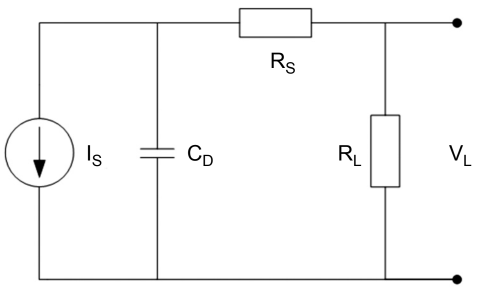

Fig. 2. Equivalent circuit of photodetector.

In the figure, I_S is the 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:

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

It seems that the major parameters which affect response time are the series resistance R_S and junction capacitance C_D. Increasing the substrate doping concentration N_D or reducing the junction area A_j can shorten the response time τ.

2.3. Improving sensitivity

The photocurrent of silicon *p*-*n* junction photodetector is expressed by:

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

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 the minority carrier diffusion lengths, X_m is the barrier width of *p*-*n* junction. From Eq. (3), it can be concluded that the photocurrent is related with the selection of material (resistivity, lifetime of minority carrier, *etc*.), junction area A_j and 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 through its high-impedance depletion layer.

It is concluded that the middle-impedance n-type (100) single-crystal silicon with long lifetime is adopted as substrate, the junction depth of p-n junction is shallow and the junction area A_j is 17.5 mm^2 [3].

2.4. Optimizing the p-n junction depth x_j

The $1/\alpha$ is the penetration depth of light wavelength λ, where α is the photoabsorption coefficient. For the devices whose junction depth is x_j, wavelength minimum producing photoelectric effect is $x_j = 1/\alpha$. The coefficient α of silicon material is about 4500−7000 cm^{-1} in the wavelength range 500−600 nm, so the junction depth x_j is between 1.4 μm and 2.2 μm. Because the penetration depth of short wavelength light is thin, the shallow junction can improve sensitivity. Considering other factors, the junction depth x_j is determined as 1.7−1.8 μm [3].

2.5. Determining the thickness of antireflection layer

In the present paper, a thick SiO_2 film is added as antireflection layer. The film can enhance sensitivity as well as improve the reliability of the devices. By studying the relationship between the relative response ($I_L/I_{L\max}$) and the thickness of antireflection layer (SiO_2) under zero bias, the thickness of the antireflection layer can be determined. It is concluded that the relative response reaches peak value when the thickness of antireflection layer (SiO_2) is 1/2 of the wavelength λ [3].

3. Analysis of the temperature characteristics

According to the scheme as before, shallow junction photodiode 2CU series (2CU stands for photodiode fabricated on the substrate of the n-type silicon) were manufactured by standard CMOS technology. Eventually, the spectrum response 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.

Since behaviors of silicon substrate change with temperature, the properties such as the dark current and photocurrent change with temperature. The operating temperature range is about 263−323 K. To increase temperature stability, the temperature characteristics of the photodetector must be investigated. Firstly, the temperature behavior of dark current at 10 V reverse bias voltage and temperature range of 253−323 K was studied. Secondly, the temperature behavior of photocurrent at zero bias and temperature range of 213−353 K was discussed.

3.1. Temperature characteristics of dark current

The dark current of photodetector is tested per 10 K at 10 V reverse bias voltage and the temperature range of 253−323 K. The relationship between dark current I_D and temperature T is shown in Fig. 3.

Three dark current components of the photodetector are generation-recombination current, traps tunneling current and band-to-band tunneling current.

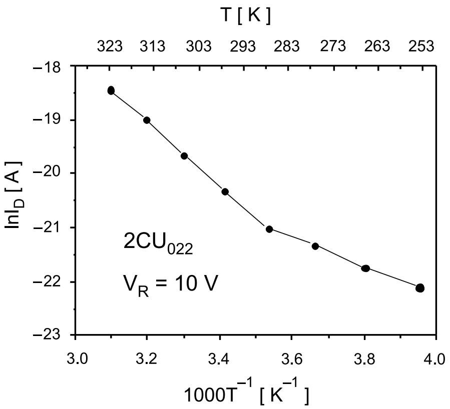

Fig. 3. Relationship between $\ln I_D$ and $1000T^{-1}$ at 10 V reverse bias voltage.

The relationship between generation-recombination current I_{gr} and temperature T is:

$$I_{\mathrm{gr}} \propto n_i \propto e^{-E_g/kT} \tag{4}$$

where n_i is the intrinsic carrier concentration, and E_g is the energy of forbidden band.

The relationship between traps tunneling current I_{tt} and temperature T is:

$$I_{\mathrm{tt}} \propto e^{(E_t - E_c)/kT} \tag{5}$$

where E_t is the trap energy, and E_c is the energy of conduction band [4, 5].

According to Eqs. (4) and (5), it can be concluded that generation-recombination current I_{gr} and traps tunneling current I_{tt} increase with increasing temperature, and traps tunneling current I_{tt} increases faster than generation-recombination current I_{gr}.

Figure 3 shows that the curve is composed of two regions: region I is the temperature range of 253−283 K; region II is the temperature range of 283−323 K. In these two regions, the natural logarithms of the dark current $\ln I_D$ change linearly with $1000\,T^{-1}$. But the slope of the line in region I is larger than that of the line in region II, in other words, dark current increases slowly with increasing temperature in region I, and it increases fast with temperature in region II.

It can be concluded that dark current is dominated by generation-recombination current I_{gr} at the temperature range of 253−283 K and is dominated by traps tunneling current I_{tt} at the temperature range of 283−323 K.

3.2. Temperature characteristics of photocurrent

The photocurrent of the photodetector is measured per 10 K at zero bias voltage and the temperature range of 213−353 K. The relationship between photocurrent I_{ph} and temperature T is shown in Fig. 4.

As shown in the figure, the photocurrent increases with increasing temperature below room temperature and it almost holds the line over room temperature. And then the measured results are analyzed theoretically.

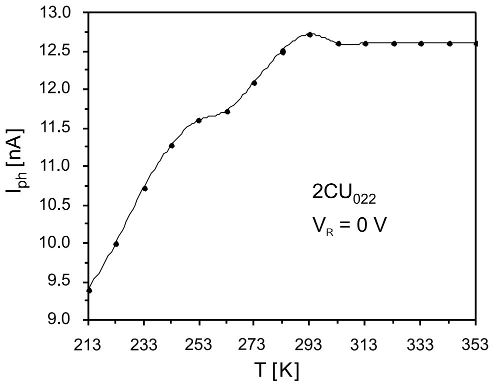

Fig. 4. Relationship between photocurrent I_{ph} and temperature *T*.

Under nonideal conditions, the current-voltage characteristics are described as:

$$\frac{q}{kT}(V - R_s I_L) = \ln\left(\frac{I_{\mathrm{ph}} - I_L}{I_0} - \frac{V - R_s I_L}{R_{\mathrm{sh}} I_0} + 1\right) \quad (6)$$

where I_{ph} is the photocurrent, R_s is the series resistance, R_{sh} is the bypass resistance, I_0 is the reverse saturation current of *p*-*n* junction, *T* is the absolute temperature, *q* is the electron charge.

For $V_R = 0$, Eq. (6) can be written as:

$$\frac{I_{\mathrm{ph}} - I_L}{I_0} + \frac{R_s I_L}{R_{\mathrm{sh}} I_0} + 1 = e^{\frac{q}{kT} R_s I_L} \quad (7)$$

Having $R_s \approx R_{\mathrm{sh}}$ on usual conditions, Eq. (7) can be rewritten as:

$$\frac{I_{\mathrm{ph}}}{I_0} + 1 = e^{\frac{q}{kT} R_s I_L} \quad (8)$$

The open voltage of photodetector is expressed as:

$$V_{\mathrm{oc}} = \frac{kT}{q} \ln\left(\frac{I_{\mathrm{ph}}}{I_0} + 1\right) \quad (9)$$

The following equation can be obtained from Eqs. (8) and (9):

$$I_L = \frac{kT}{R_s q} \ln\left(\frac{I_{\mathrm{ph}}}{I_0} + 1\right) = \frac{V_{\mathrm{oc}}}{R_s} \quad (10)$$

Equation (10) can be used to explain the curve of Fig. 4. The bandgap energy of silicon substrate becomes narrow with increasing temperature, which makes open voltage V_{oc} decrease. The series resistance R_s is the high resistivity region, which has freezing effect of carriers at the lower temperature. In the temperature range of 213−293 K, the freezing effect is obvious, and the resistance of R_s decreases fast with increasing temperature. Photocurrent I_L is dominated by R_s, and not V_{oc}, decreasing with increasing temperature. Consequently, photocurrent I_L increases as temperature increases below room temperature [6].

At the temperature range of 293−353 K, the freezing effect can be neglected and photocurrent I_L is dominated by V_{oc}, and not R_s. Consequently, photocurrent I_L almost holds the line over room temperature.

Over the temperature range of 263−323 K, the amplitude variation of photocurrent is less than 10%. Consequently, the photodetector fulfils quality requirements.

4. Conclusions

Adopting *n*-type (100) single-crystal silicon with middle-impedance and long lifetime as a substrate, we successfully developed green photodetectors with low dark current, high sensitivity and large SNR, by optimizing the above five aspects. The temperature characteristics of the dark current and photocurrent at zero bias are emphatically investigated. Firstly, the temperature behavior of dark current at 10 V reverse bias voltage and temperature range of 253−323 K was studied. Secondly, the temperature behavior of photocurrent at zero bias and temperature range of 213−353 K was discussed.

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References

[1] LIU ENKE *et al.*, *Semiconductor Physics*, 7th Edition, Electronic Industry Publishing House, Beijing, 2003, pp. 162−192 (in Chinese).

[2] ZHANG SHENGCAI *et al.*, *The analysis for reliability and life of the photo-sensitive diodes*, Journal of Optoelectronics – Laser **14**(5), 2003, pp. 466−469 (in Chinese).

[3] XIANSONG FU, SUYING YAO, JIANGTAO XU, YAO LU, YUNGUANG ZHENG, *Study on high signal-to-noise ratio (SNR) silicon p-n junction photodetector*, Optica Applicata **36**(2−3), 2006, pp. 421−428.

[4] HAO GUO-QIANG *et al.*, *Temperature behavior of* $In_{0.53}Ga_{0.47}As$ *PIN photodetectors*, Journal of Functional Materials and Devices **11**(2), 2005, pp. 192−196 (in Chinese).

[5] OBREJA V.V.N., *On the leakage current of present-day manufactured semiconductor junctions*, Solid-State Electronics **44**(1), 2000, pp. 49−57.

[6] YAN YANG *et al.*, *Design of high performance Si photodetector and analyses of temperature characteristic*, Journal of Optoelectronics – Laser **18**(1), 2007, pp. 46−49 (in Chinese).

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