The Simulation Analysis of a Ge/Si Waveguide Avalanche Photodetector

Zhen Wang [a], Ting Wang [b], Chaoyu Du [c], Wei Wang [d], Li Chen [e]

College of Electronics Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

[a]wangzhen@cqupt.edu.cn, [b]1126338473@qq.com, [c]779649389@qq.com,

[d]wangwei@cqupt.edu.cn, [e]446219487@qq.com

Abstract

A Ge/Si waveguide avalanche photodetector (APD) is proposed in the paper, in which, in order to increase the light absorption rate and photocurrent, waveguide is incorporated into a conventional Ge/Si APD. In this device, light propagating along the Si waveguide layer is evanescently absorbed by an overlaying Ge layer grown on it. The structure and performance of the device is simulated by silvaco software, the simulation results show that the avalanche breakdown voltage is -28V, maximum internal quantum efficiency is 80%, the higher degree of the responsibility is obtained in the range of 1150nm~1600nm, the wavelength of peak responsibility is 1310nm, the highest responsibility is 0.74A/W.

Keywords

Ge/Si; APD; waveguide; light absorption rate; photocurrent

1. Introduction

With the advances of the fiber-optic communications technology and the military technology, semiconductor photodetectors enter the wide field of application[1]. APDs had high sensitivity, large dynamic range, high responsibility become a key element in the optical communication system of 0.92 ~ 1.65um band, so the technology of APD detection has been rapid development. Currently, III-V compound APDs can be used in the optical communication system of 1.3 ~ 1.5μm band and possess high-speed, high responsibility, but they are expensive, low-bandwidth gain[2]. So they cannot popularize. In contrast, Ge/Si APDs developed based on traditional Si-based APD not only have mature process, low cost, but also nicely combine the advantages both germanium and silicon materials. Because they use germanium material had narrow band gap as a light absorption layer to improve long-wavelength sensitivity; while they also use Si material had the desired hole/electron ionization ratio (k<0.1) as a multiplication layer to improve avalanche multiplication gain[3]. In recent years, Ge/Si APDs increasingly become a hot topic.

A normal Ge/Si APD with a conventional structure of separate absorption, charge, and multiplication (SACM) has been demonstrated the light absorption rate are limited by the thickness of absorption layer. To solve this issue, to integrate Si waveguides into this structure with evanescent-coupling scheme. The paper reports a Ge/Si waveguide APD, and demonstrates the design and simulation analysis of the device.

2. Device Structure and Design

In the Ge/Si SACM APD, In order to improve the light absorption rate of the device, we need to increase the thickness of the absorption layer, which results that the transit-time of carrier increases and degrades the response speed of the device. However, in the Ge/Si waveguide APD, the improvement of light absorption rate only rely on the length of absorption layer and not its thickness due that light enters the device from the side of the device. So Ge/Si waveguide APD not only obtains low carrier transit-time, but also gets high light absorption rate. Fig.1 shows the three-dimensional structure of the Ge/Si waveguide APD.

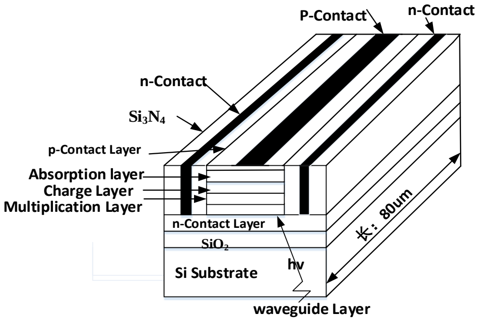

Fig.1 Perspective view of the Ge/Si waveguide APD

In Fig.1, the light propagating along the Si waveguide layer is evanescently absorbed by an overlaying Ge layer grown on it, so the length of the absorption layer becomes a key factor that influences the light absorption rate. When the length of the absorption layer is 70um, the light absorption rate can get 90%[4-5]. In this paper, the length of the absorption layer is designed 80um.

If the n-contact is applied by a positive voltage while the p-contact is applied by a negative voltage, Ge layer generates carriers by absorbing the photons of 1.3 ~ 1.5μm band, namely electron- hole pairs. Under the influence of the applied electric field, the electron-hole pairs traverse the waveguide layer, perpendicularly arrive to the multiplication layer. The carriers obtained enough energy in the high electric field of the multiplication layer collide with the lattice, resulting an avalanche effect, thereby the photocurrent sharply increases. In the above process, the photon flux direction is along the waveguide layer, while the carrier transport direction is perpendicular to the waveguide layer, both directions exactly are perpendicular to each other and cannot disturb each other, which greatly reduces the dark current of the device. The sharp contrast, in the Ge/Si SACM APD, the direction of the light absorption and carrier transport direction are the same direction, which may lead that the carrier multiplication occurs in the absorption layer, even very a small number of carriers between the absorber layer and the multiplication layer causes great loop feedback current[6]. It will not only increases the dark current of the device, but also reduces the bandwidth gain of the device.

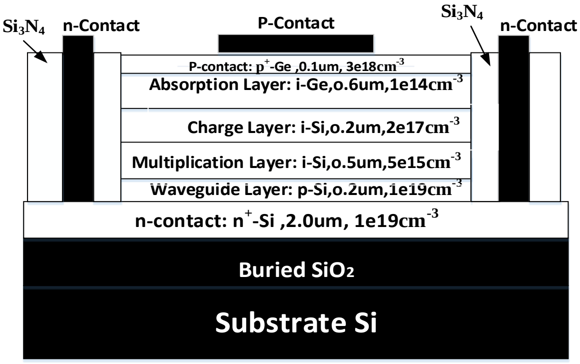

Fig.2 Sectional view of the Ge/Si waveguide APD

Fig.2 shows the Sectional view of the Ge/Si waveguide APD. In Fig.2, the functional layers of the device from top to bottom: an p^+ electrode layer, Ge absorbing layer, Si charge layer, Si multiplication layer, Si waveguide layer, an n^+ electrode layer. In order to ensure the applied voltage can be applied to the effective working area, two electrode layers are high-doped, the p^+ electrode layer had a thickness of 0.1μm is a dopant of $3\times10^{18}cm^{-3}$, the n^+ electrode layer had a thickness of 2μm is a dopant of $1\times10^{19}cm^{-3}$. The thickness of Ge absorbing layer is 0.6μm due to the light absorption rate is not determined by the thickness of the absorbing layer, thereof the thickness can be suitably reduced to improve the response speed. The thickness of charge layer always is 0.2um.The more the thickness of multiplication layer is big, the electric field strength reached the breakdown will be greater, which easy to cause tunneling. Thus the thickness of the Si multiplication layer is set at 0.5μm. The typical thickness of the Si waveguide layer is about 0.2μm. Anti-reflective material wrapped around the n^+ electrode is Si_3N_4, to prevent the light reflected by the surface of the device. The doping profile of the device as shown in Fig.3.

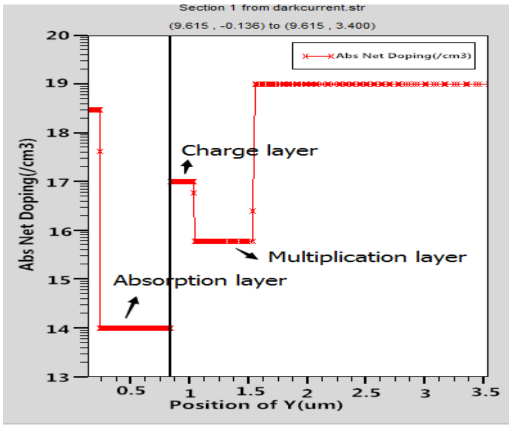

Fig.3 Doping of the Ge/Si waveguide APD

In Fig.3, the dopant of the charge layer slightly higher than the absorption layer and multiplication layer, which has two main functions: One is to ensure multiplication layer in a high electric field state, otherwise the high electric field region will fall in the charge layer; the second is to mitigate the potential difference between absorption layer had a low electric field and multiplication layer had a high electric field.

3. the Analysis and discussion of the performance of the device

3.1 Electric field of the device

Simulation of electric field distribution of the Ge/Si waveguide APD is shown in Fig.4.

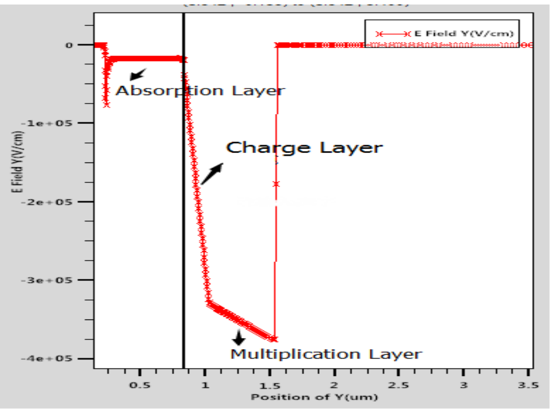

Fig.4 Electric field distribution of the Ge/Si waveguide APD

In Fig.4, the electric field strength of the Ge absorption layer is 35KV/cm, in principle, it is consistent with the requirement of the electric field strength of Ge absorption layer(under the influence of an applied voltage, when the electric field strength of near the PN junction is less than10^5V/cm, PN junction does not occur avalanche multiplication). Fig.4 shows the electric field of multiplication layer is 3×10^5 V/cm, the threshold value occurring avalanche multiplication is 10^5V/cm and the electrical field reaches the critical value, while less than 10^6V/cm that critical value of occurring Zener breakdown.

3.2 Current characteristics of the device

The dark current of photodetector mainly comes from electrical signal, noise, lack of lattice and some tunneling current[7]. Photocurrent mainly decides by the light intensity, the light absorption rate, the avalanche multiplication gain and other factors[8]. The simulation of photocurrent and dark current of the Ge/Si waveguide APD shown in Fig.5.

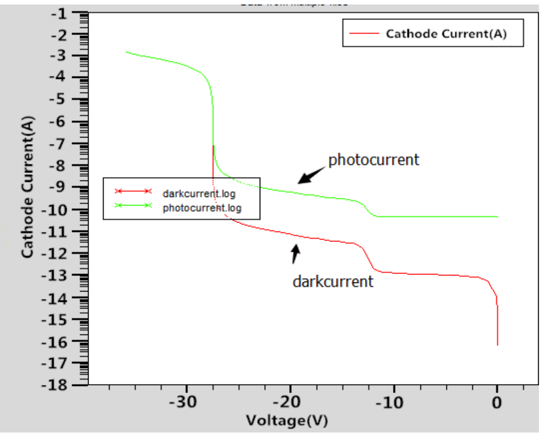

Fig.5 Photocurrent and dark current of Ge / Si waveguide APD

In Fig.5, when the bias voltage falls in the range of 0 ~ -10V, the photocurrent is small due to low carrier mobility. When the bias voltage is in the range of -10 ~ -15V, the photocurrent and dark current slightly enhance. The improvement of photocurrent mainly due that the multiplication layer is completely depleted. Dark current increases due to the depletion layer extends to the Ge/Si heterojunction, where the lack of lattice will be more than anywhere else, more prone to dark current. When the bias voltage is in the range of -27V ~ -29V, the pn junction is fully depleted, the device mainly occurs the avalanche multiplication, which prompts photocurrent to rapidly boost. The breakdown voltage of the Ge/Si waveguide APD is in range of -27V ~ -29V in this paper. In Fig.5, when the bias voltage is -28V, the photocurrent reaches 1×10^{-4} A/cm, the dark current reaches 1×10^{-7} A/cm. So the photocurrent of the Ge/Si waveguide APD has been greatly improved.

3.3 The responsibility of the device

APDs have a high degree of response due to their internal avalanche gain. The formula of Response is defined as:

$$\mathrm{R} = \frac{I_{ph}}{P_{opt}} = \frac{\lambda\,\eta}{hv}$$

Wherein, I_{ph} is the photocurrent generated by the incident optical, P_{opt} is the optical power of the incident light, η is the quantum efficiency.

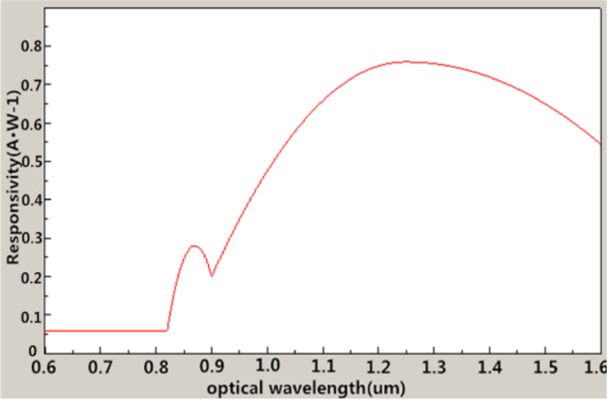

Fig.6 responsibility of the Ge/Si waveguide APD

The simulation of responsibility of the Ge/Si waveguide APD shown in Fig.6. The APD for 1.1 ~ 1.6μm band has high sensitivity, the peak wavelength is 1.3μm. When the wavelength of incident light is 1.3μm, the response reaches a maximum of 0.74A/W.

The quantum efficiency of APD is the number of electron-hole pairs generated by each incident photon. It is defined as:

$$\eta = \frac{I_{\text{ph}}}{q\phi} = \frac{I_{ph}}{q}(\frac{hv}{P_{opt}})$$

In this formula, I_{ph} is the photocurrent generated by incident light, P_{opt} is the optical power of incident light, hv is the incident photon energy ($h = 6.63\times10^{-34} J/s$).If there is no photon loss in the depletion region, the quantum efficiency is l. However, for an actual APD, the quantum efficiency is unlikely to be 1. Coupling loss of light in the APD is inevitable, so the formula of quantum efficiency is also defined as:

$$\eta = (\frac{I_o}{I_P})(\frac{hv}{\lambda})R_{APD}$$

When the incident optical wavelength is 1.3μm, data obtained based on the simulation can calculate the quantum efficiency of 80%.

4. Conclusion

In the paper, we design a Ge/Si waveguide APD, analyze the structural features of the device and analyzes the simulation of its light and dark current, responsibility and quantum efficiency. The simulation results show that the structure has greatly enhanced the photocurrent and the quantum efficiency of the device, and has a high degree of response in the range of 1150 ~ 1600nm wavelength.

References

[1] Wang Wei, Bai Chen Xu, Feng Qi, et al., Effect of the Structure Parameters of the Silicon PIN Photodetector on its Properties[J]. Semiconductor Optoelectronics, 2013, 34(3): 379-382.

[2] S. Zhu, K.W. Ang, S.C. Rustagi, et al., Waveguided Ge/Si avalanche photodiode with separate vertical SEG-Ge absorption, lateral Si charge, and multiplication configuration[J]. IEEE Electron Device Letters, 2009, 30(9): 934-936.

[3] Wang Wei, Feng Qi, Wu Wei, et al., Analysis and Simulation of Process and Performance of Silicon Avalanche Photodiode [J], Infrared and Laser Engineering, 2014, 43(1): 140-144.

[4] A. Ramaswamy, N. Nunoya, T. Yin, et al., Microwave Characteristics of Ge nip waveguide photodetectors on Silicon-on-Insulator Substrate[C], Proceedings of LEOS Annual Meeting Comference. 2009: 660-661.

[5] Gu Yan Xi, Research of the Vertical Directional Coupling Photodiode [D]. University of Electronic Science and Technology, 2013.

[6] W. Xiaoxin, and L. Jifeng, Step Waveguide Design for Efficient Coupling to Integrated Ge/Si Avalanche Photodetectors[C], 2010 7th IEEE International Conference on Group IV Photonics (GFP)，2010, 99-101.

[7] Kang Y, Morse M, Paniccia M J, et al. Monolithic Ge/Si avalanche photodiodes[C]// Group IV Photonics, 2009. GFP '09. 6th IEEE International Conference on. IEEE, 2009:25 - 27.

[8] Zhang Yu, Study on GeSi-based Waveguide Photodetector [D]. TianJin Polytechnic University, 2007.