Optically controlled SiCGe/SiC heterojunction transistor with charge-compensation layer*

Pu Hong-Bin(蒲红斌)†, Cao Lin(曹 琳), Chen Zhi-Ming(陈治明), and Ren Jie(任 杰)

Department of Electronic Engineering, Xi'an University of Technology, Xi'an 710048, *China*

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A novel optically controlled SiCGe/SiC heterojunction transistor with charge-compensation technique has been simulated by using commercial simulator. This paper discusses the electric field distribution, spectral response and transient response of the device. Due to utilizing p-SiCGe charge-compensation layer, the responsivity increases nearly two times and breakdown voltage increases 33%. The switching characteristic illustrates that the device is latch-free and its fall time is much longer than the rise time. With an increase of the light power density and wavelength, the rise time and fall time will become shorter and longer, respectively. In terms of carrier lifetime, a compromise should be made between the responsivity and switching speed, the ratio of them reaches maximum value when the minority carrier lifetime equals 90 ns.

Keywords: SiCGe/SiC, transistor, charge-compensation, responsivity

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1. Introduction

As we know, conventional electronic control systems are susceptible to electromagnetic interference (EMI) problems, which leads to destroying the reliability of control signals. Based on this viewpoint, a photoelectric isolation method is put forward to effectively resolve the EMI problem. Meanwhile, the realization of direct optically controlled power device is the first major step for photonic power electronic systems. Therefore, feasibility of this kind of device is coming on the agenda of scientific research.

Silicon carbide (SiC) has been verified as a promising semiconductor that can be used in a harsh environment owing to its superior material properties. However, SiC is not optically active at the visible and near infrared (IR) wavelengths where communication light sources are readily available, hence it is limited to applications in optically-triggered devices.

In order to realize the light-activation of SiC power switching devices, a hybrid approach that combines a silicon photo-receiver module with SiC power Darlington transistor has been proposed.[1] In this hybrid Si/SiC device, Darlington transistor is activated by photocurrent coming from an individual Si photodiode. However, the EMI problem may still exist because the direct input signal of the Darlington transistor is actually an electronic signal. To completely resolve the EMI problem, we have proposed a light-activated SiC Darlington transistor[2] with narrow bandgap material SiCGe served as base layer, which realizes light-activated power switches using common light source. A series of works have been done to grow ternary alloy SiCGe on SiC substrates by hot-wall chemical vapour deposition (CVD)[3−5] method. The samples exhibit island growth mode at lower temperature, and the growth mode transforms into layer by layer mode via changing the form and density of island as the growth temperature increases.[6] Intense visible luminescence induced by SiCGe films grown on SiC substrate is observed at room temperature,[7] and the important data such as energy band-gap and interior structure of SiCGe thin films have been obtained. Taking into account practice techniques, Lü *et al.*[8] and Zhu *et al.*[9] have proposed and improved a monolithically integrated SiCGe/SiC light-activated Darlington transistor, in which SiCGe/SiC heterojunction pn diode is employed to drive SiC Darlington transistor. The optically controlled lateral n-SiC/p-SiC/n-SiCGe power transistor with p-SiC charge-compensation layer has been put forward,[10] in which optoelectronic peak responsivity

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†Corresponding author. E-mail: puhongbin@xaut.edu.cn

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of the device can reach 330 mA/W at the wavelength 0.5 μm and 2 V bias voltage, but optical gain is still low.

In this paper, we propose a new design of the optically controlled SiCGe/SiC power transistor with 4H-SiC as emitter, SiCGe as base, collector and charge compensation layer. Feasibility of the new design structure is successfully tested by using a two-dimensional device simulator. We can predict that the transistor with SiCGe as light absorption layer in the base and collector region and charge-compensation layer forms a two dimensional electric field distribution, thus high optical gain can be realized.

2. Device structure and principle of operation

As shown in Fig. 1, the devices with a floating base have two lateral electrodes of emitter and collector. Higher emitter efficiency can be realized by the n-SiC/p-SiCGe heterojunction at the emitter–base junction, since holes flowing from the base to emitter are blocked by the high barrier in the valence band, therefore the collector current of the proposed n-SiC/p-SiCGe/n-SiCGe transistor is significantly larger than that of the n-SiC/p-SiC/n-SiCGe transistor.

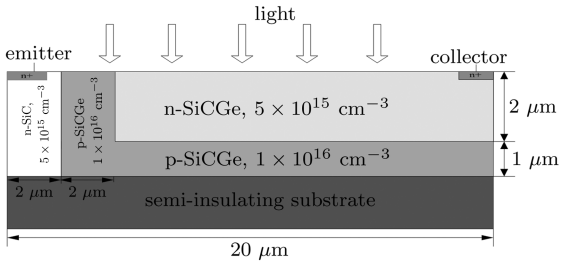


Fig. 1. Structural scheme of the SiCGe/SiC phototransistor.

The bottom p-type SiCGe layer acts as a charge-compensation layer which makes the electric field distribution of the collector region two dimensional. With the interactive of vertical and parallel pn junction, the rectangular electric field distribution is formed. In comparison with conventional triangular electric field distribution, device sensitivity and responsivity increase a lot. The doping and thickness of these layers have been designed to realize the charge-balance.[11] i.e., the total positive charge contributed by the p-SiCGe layer is equal to the total negative charge contributed by the top n-SiCGe layers. The lateral charge-compensation structure offers the simplicity of controlled epitaxial growth to realize charge-balance, rather than the vertical one.

In the blocking or open state, the applied voltage is supported by the reverse biased pn junction between the p-body and n-drift regions. When the trigger beam falls on the device, SiCGe layer absorbs it and generates electron–hole pairs by photogeneration. They are mobilized by the local electric field and attracted by the two electrodes via a conducting channel. If the light beam is sustained the conductivity is sustained. However, when the light shuts off, the carriers are recombined among themselves and the switch goes back to a blocking state.

3. Simulation results and analysis

In order to achieve the realistic results, several important material parameters used in Silvaco Atlas[12] are adjusted to meet the closest agreement with published material data of 4H-SiC.

The hot-wall CVD is employed to grow the SiCGe on 4H-SiC substrates. Gas source is a mixture of silane (SiH_4), germane (GeH_4) and propane (C_3H_8). Hydrogen (H_2) with high purity is used as a carrier gas. The growth pressure is maintained at 260 Pa with the flow rates of 30, 15, 20 and 1000 SCCM for SiH_4 (10% in H_2), GeH_4 (5% in H_2), C_3H_8 (10% in H_2) and H_2, respectively. The growth temperature and time are 700 °C and 1 hour respectively, the experimental apparatus and the basic conditions used in this work have been presented in details in our earlier work.[3] The UV (ultraviolet)–VIS (visible) optical transmission spectra of the samples are recorded by Shimadzu UV3150 spectrophotometer. Figure 2 shows the absorption spectra and Tauc curve of the sample. According to the Tauc relationship, the calculated band gap of the SiCGe layer is 1.65 eV. Since the investigation of SiCGe alloys is still at primary stage, the ionization coefficient necessary for simulation has no experimental data, assuming that the ionization coefficient of the SiCGe alloys is used for the linear ionization coefficient relationship between SiC and Ge.

Due to device investigation still being at a primary stage, theory verification is difficult, thus simulation is made by means of a comparison method in order to illustrate the advantage of the device. Simulation condition is the same except with and without the p-type SiCGe layer.

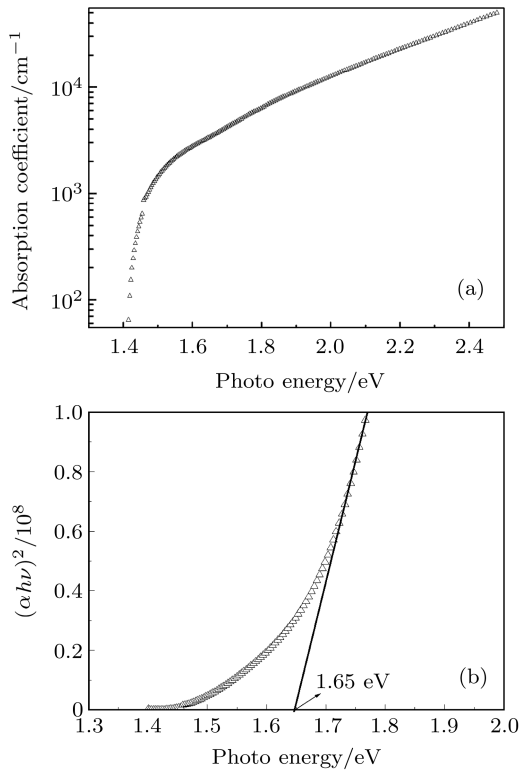


Fig. 2. The optical absorption spectra of SiCGe film and Tauc curve. (a) Optical absorption spectra and (b) Tauc curve.

When charge-compensation is satisfied ($qN_{\rm D} = -qN_{\rm A}$) in the drift region, the Poisson equation can be written as

$$\begin{aligned}\boldsymbol{\nabla}^2\phi &= \frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}\\ &= -\frac{\rho}{\varepsilon}\\ &= -\frac{qN\,(x,y)}{\varepsilon}\\ &= -\frac{q\,(N_{\rm D}+N_{\rm A})}{\varepsilon}\\ &= 0. \end{aligned} \tag{1}$$

For that reason,

$$E = -\boldsymbol{\nabla}\phi \Rightarrow E = \text{constant}. \tag{2}$$

So when charge-balance is satisfied, the drift region completely depleted, then relatively flat electric field distribution can be obtained as shown in Fig. 3.

As the incident light illuminates horizontally, the photogeneration rate will be a function of the horizontal distance as shown in Fig. 4, when we consider that the optical decay length is less than the collector region thickness. Then the total photogeneration rate across the two depletion region can be written as

$$\begin{aligned}G_1 &= \int_0^b (1-R)\frac{P}{hv}\alpha\,{\rm e}^{-\alpha x}\,{\rm d}x\\ &= (1-R)\frac{P}{hv}(1-\,{\rm e}^{-\alpha b}),\end{aligned} \tag{3}$$

$$\begin{aligned}G_2 &= \int_e^b (1-R)\frac{P}{hv}\alpha\,{\rm e}^{-\alpha x}\,{\rm d}x\\ &= (1-R)\frac{P}{hv}\left(1-\,{\rm e}^{-(b-e)\alpha}\right),\end{aligned} \tag{4}$$

where P is the power of the incident light, h is Planck's constant, ν is the frequency of the incident light, α is the effective absorption coefficient of the material, R is refractive index. Most of the photocurrent

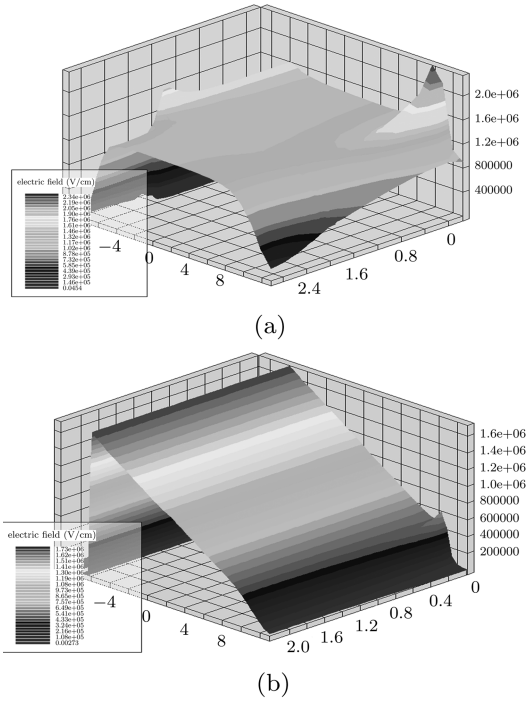


Fig. 3. Electric field distribution at breakdown voltage: (a) with charge compensation layer and (b) without charge compensation layer.

should be contributed by the drift current in the depletion region due to the relatively small diffusion length, so the responsivity can be expressed as

$$\begin{aligned}R &= \frac{\beta I}{P_{\rm in}}\\ &= \frac{\beta q}{P_{\rm in}}\int_\lambda\left[c\int_0^b \alpha\,{\rm e}^{-\alpha x}\,{\rm d}x\right.\\ &\quad\left.+\,(d-c)\int_e^b \alpha\,{\rm e}^{-\alpha x}\,{\rm d}x\right]{\rm d}\lambda\,,\end{aligned} \tag{5}$$

where β is the internal gain of the transistor, the position of the e and c can be calculated with the doping concentration and the applied voltage as shown in Fig. 4. With p-type SiCGe compensation layer forming two dimensioned electric field distributions, responsivity increases a lot at relative low voltage. Flat electric field distribution at high voltage also quickly

separates the photogenerated electron–hole pairs, thus higher responsivity can be obtained. The simulated light responsivity of this device has a maximum value at wavelength around of 0.50 μm, obtaining 70 A/W when reverse bias voltage is 2 V nearly two times bigger than without one.

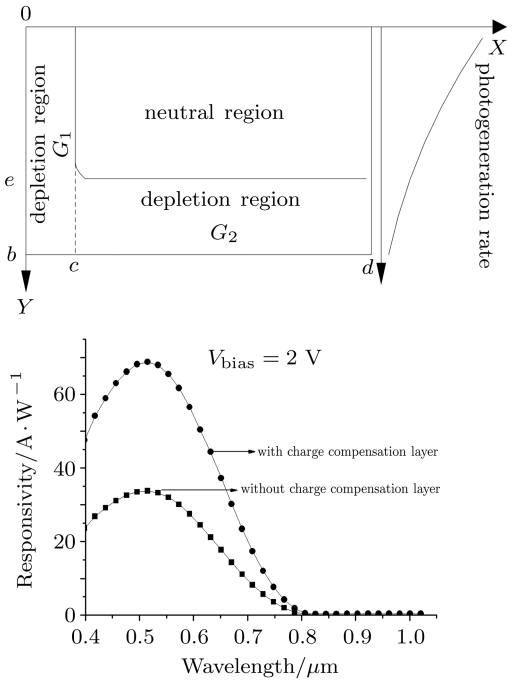


Fig. 4. Schematic diagram of light absorption layer and calculated spectral response.

Similar superjunction[13] technology, derived from the lateral RESURF idea, breakdown voltage ($V_{\rm R}$) can be increased and simply given by

$$V_{\rm R} = E_{\rm C} \cdot t_{\rm drift}, \tag{6}$$

where $E_{\rm C}$ is the critical electric field of SiCGe, $t_{\rm drift}$ is the length of the drift layer. Breakdown voltage of charge compensation phototransistor ($V_{\rm R}$ = 600 V) with p-type SiCGe layer is 33% better than that of the without one ($V_{\rm R}$ = 450 V) as shown in Fig. 5.

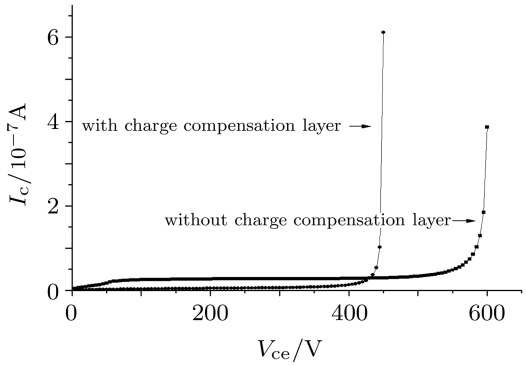


Fig. 5. Reverse I–V character of both with and without p-type SiCGe layer.

The switching character was calculated with mixed circuit-device simulator. Common emitter circuits are used in the simulation and load resistance is well designed.

Unlike light triggered thyristors and optothyristors[14] in which inherent thyristor like latch-up problems and a semi-insulating thick layer make it turn off slowly and have a large voltage drop.[15,16] It shows that the devices are latch-free devices, turning off the trigger light ensures that turn-off of the device and fall time is much longer than the rise time as shown in Fig. 6.

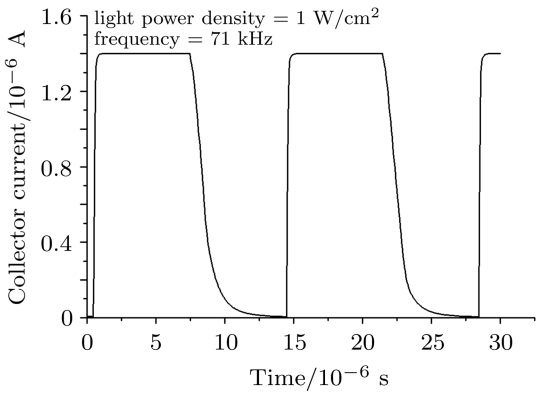


Fig. 6. Switching character of the device.

The switching character of the device relies on the carrier photogeneration rate, which equally relies on the light wavelength, material absorption coefficient and surface reflectivity. However, both material absorption coefficient and surface reflectivity are nonlinear functions of the wavelength, which, in turn influence the switching character.

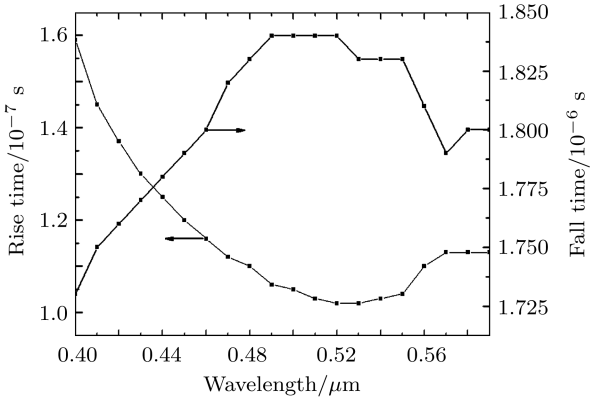


Fig. 7. Rise and fall time variation with wavelength.

With the increase of wavelength at the same optical power, the number of photons increases and surface light reflectivity decreases, thus rise time decreases and fall time increases as shown in Fig. 7. Absorption coefficient decreases rapidly at wavelength

greater than SiCGe absorption edge (about 520 nm), photogeneration rate decreases and switching character changes.

Higher optical power density enables higher photogeneration rate in the light absorption region thus quickly builds-up current conduct channel, hence resulting in shorter rise time. On the other hand, higher photogenerated density takes longer time to deplete by recombination thus translates into higher fall time.

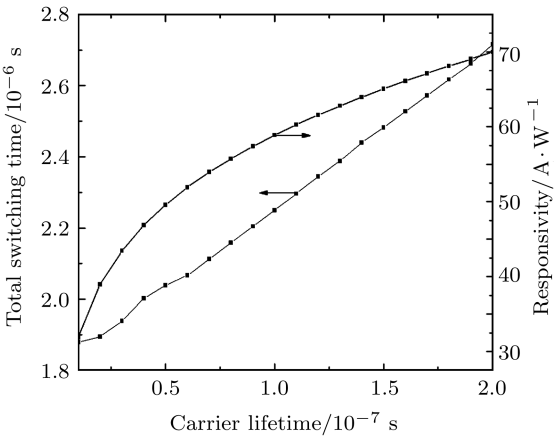


Fig. 8. Device responsivity and switching speed variation with carrier lifetime.

Carrier lifetimes have a strong influence on the device responsivity and switching speed (sum of rise and fall time), both increase with the increase of carrier lifetime as shown in Fig. 8. Desired optically-triggered power devices ask higher responsivity (translate into lower optical triggering power density) and lower total switching time, so trade-off must be made between them. The calculated ratio of the two quantities reaches maximum value when minority carrier lifetime is equal to 90 ns.

4. Conclusions

The optically controlled SiCGe/SiC heterojunction transistor with a p-type SiCGe charge compensation layer has been discussed. Assuming the theoretical maximum internal quantum efficiency, we have observed nearly two times the responsivity increase. With flat electric field distribution, we can support higher reverse bias during off-state. The switching character illustrates that devices are latch-free device, turning off the triggering light source ensures turn-off the device. Higher optical power density enables us to quickly build-up current conduction channel thus shorter rise time, but excessive photogenerated carrier cause higher fall time. The relationship between switching speed and wavelength is ascribed to wavelength caused absorption coefficient and surface reflectivity change. The SiCGe minority carrier lifetime 90 ns gives better trade-off between device responsivity and switching speed.

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