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Si/SiC heterojunction optically controlled transistor with charge compensation layer

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Abstract. A novel n-SiC/p-Si/n-Si optically controlled transistor with charge compensation layer has been studied in the paper. The performance of the device is simulated using Silvaco Atlas tools, which indicates excellent performances of the device in both blocking state and conducting state. The device also has a good switching characteristic with 0.54μs as rising time and 0.66μs as falling time. With the charge compensation layer, the breakdown voltage and the spectral response intensity of the device are improved by 90V and 33A/W respectively. Compared with optically controlled transistor without charge compensation layer, the n-SiC/p-Si/n-Si optically controlled transistor with charge compensation layer has a better performance.

1 Introduction

With electronic products are wide application, electromagnetic interference (EMI) effects become a critical issue for safety and reliability in power electronic systems. Photoelectric isolation method is an effective way that used to resolve electromagnetic interference problem[1]. Although Si-based light controlled transistor has been developed for many years, its physical properties have obvious limitations in high temperature, high frequency and high power applications. With large wafer-size silicon carbide (SiC) wafer localization and mature of high quality 6H-SiC and 4H-SiC epitaxial technology, SiC power devices set off an upsurge study.

However, SiC is not optically active at the near IR wavelength range, where light sources are readily available for optical communication[2]. In order to realize light-activation of SiC power switching devices, a hybrid approach that combines a silicon photo-receiver module with a SiC power darlington transistor have been proposed[3]. In this hybrid Si-SiC device, the darlington transistor is activated by photocurrent output from an individual Si photodiode. Therefore, the EMI problem may still exist because the direct input of the darlington is actually an electronic signal. To prevent the EMI problem absolutely, we proposed light-activated SiC transistors in earlier work[4-5]. In which by using narrow bandgap material SiCGe as base layer, the device can realize light-activated power switches for common light source.

In this paper, a novel optically controlled SiC power transistor structure based on the 4H-SiC/Si heterojunction and charge compensation layer is proposed to improve spectral response range and efficiency of the device. By employing the device simulator Silvaco Atlas, we have simulated the performances of this device based on SiC/Si heterojunction and charge compensation layer.

2 Device structure

The structure schematic of n-SiC/p-Si/n-Si heterojunction optically controlled transistor with and without compensation layer are shown in figure 1. The emitter electrode and collector electrode are locating at left and right side respectively. The optical window between emitter and collector is passivated by Si_3N_4 to reduce reflectivity of light. The heavily doped 4H-SiC is used as emitter region material. The emitter region of device is 3.0μm in thickness and 2.0μm in width. The n-SiC/p-Si heterojunction in the device working as emitter junction can improve the injection efficiency of the emitter and reduce the energy of the triggering light. To wider the light response range, silicon is used as material of base region and collector region. The base region is 3.0μm in thickness and 2.0μm in width. The base current is supported by photocurrent of collector junction. The width of collector region is 17μm. In order to improve the light absorption efficiency, the thickness of the collector region must be longer than the depth of light absorption. As shown in figure 1(b), the thickness and doping concentration of compensation layer under the silicon collector region should be designed basing on charge-balance theory. Under the effect of compensation layer, there is a two-dimensional electric field in silicon collector region. The two-dimensional electric field can help improve the blocking voltage and spectral responsivity of the transistor. To avoid charge imbalance affected by the substrate-assisted depletion, the semi-insulating SiC is used as substrate.

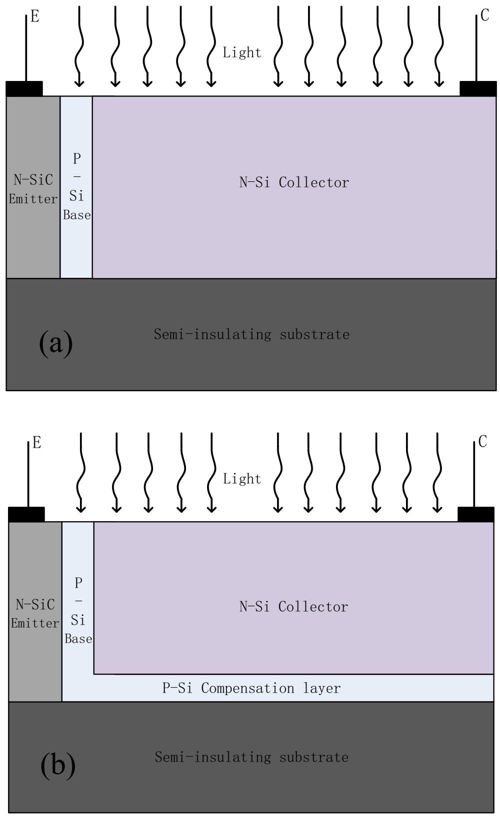

Figure 1. Structure schematic of the Si/SiC heterojunction optically controlled transistor (a) without charge compensation layer (b) with charge compensation layer.

3 Simulation and discussion

In order to achieve the realistic results, several important material parameters used in Silvaco Atlas were adjusted to obtain the closest agreement with published material data of 4H-SiC[6-8]. The major parameters used in the paper are shown in table 1.

Table 1. Major parameters used in the paper.

Parameter	value	unit
Eg300	3.26	eV
Affinity	3.8	eV
Eab	0.2	eV
Edb	0.1	eV
Augn	5×10^{-32}	cm^6/s
Augp	2×10^{-32}	cm^6/s
Permittivity	9.66	-
Gvb	4	eV
Gcb	2	eV

When the device is under blocking condition, there is a forward bias voltage fall over the collector junction. As the doping concentration of collector region is lighter than the doping concentration of base region, the depletion layer is mainly broadening in collector region. The three-dimensional electric field distributions of the optical transistors under the blocking condition both with and without compensation layer are shown in figure 2. As the comparison between the electric field of two devices in figure 2(a) and figure 2(b), the electric field distributes more uniformly in figure 2(b). Due to the existence of charge compensation layer, the depletion region in figure 2(b) is broadening in two directions. The charge compensation layer helps extend the collector junction in horizontal direction, which is helpful to form a more electric field in vertical direction. As the device with the charge compensation layer is designed according with the charge-balance theory (qN_D=-qN_A), the 2D Poisson equation can be write as

$$\nabla^2\phi=\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=-\frac{\rho}{\varepsilon}=-\frac{qN(x,y)}{\varepsilon}=-\frac{q(N_D+\mathrm{N_A})}{\varepsilon}=0 \quad (1)$$

where ρ is the charge density. The electric field in drift region can be write as

$$E=\nabla\phi=\text{constant} \quad (2)$$

which means the drift region is completely exhausted and the distribution of the electric field should be more uniform.

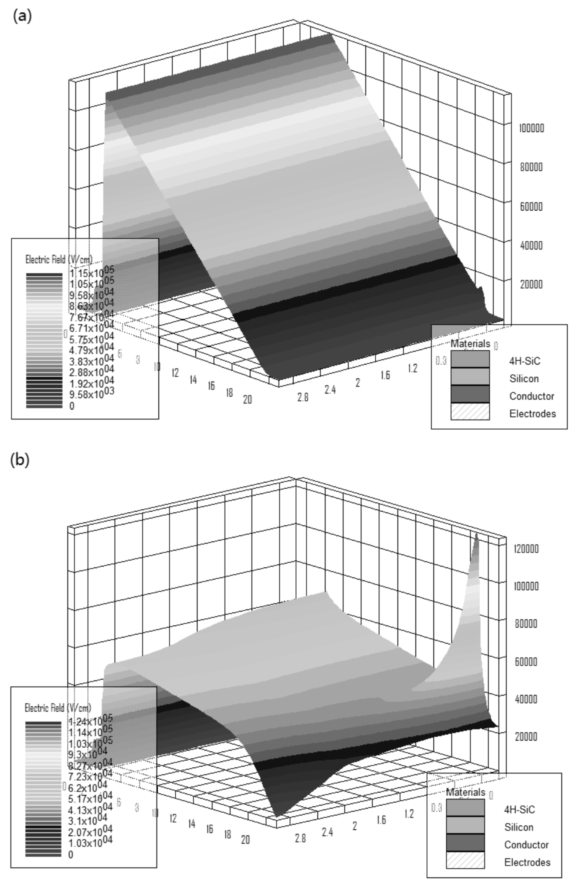

Figure 2. Electric field distribution of Si/SiC heterojunction optically controlled transistor (a) without charge compensation layer (b) with charge compensation layer.

As two-direction distributed electric field of optical transistor with charge compensation layer is more uniform than the one without charge compensation layer, the transistor with charge compensation should have higher breakdown voltage and the breakdown voltage should be more stable when the doping concentration of collector region fluctuating. Simulation results of blocking characteristics for two transistors with different collector region doping concentration are shown in figure 3. As the existence of charge compensation layer, the uniformly distributed electric field makes the breakdown voltage of transistor with charge compensation layer be higher than transistor without charge compensation layer. And the breakdown voltage of transistor with charge compensation layer is more stable than transistor without charge compensation layer when the doping concentration of collector region is changing from $5x10^{14}cm^{-3}$ to $1x10^{16}cm^{-3}$.

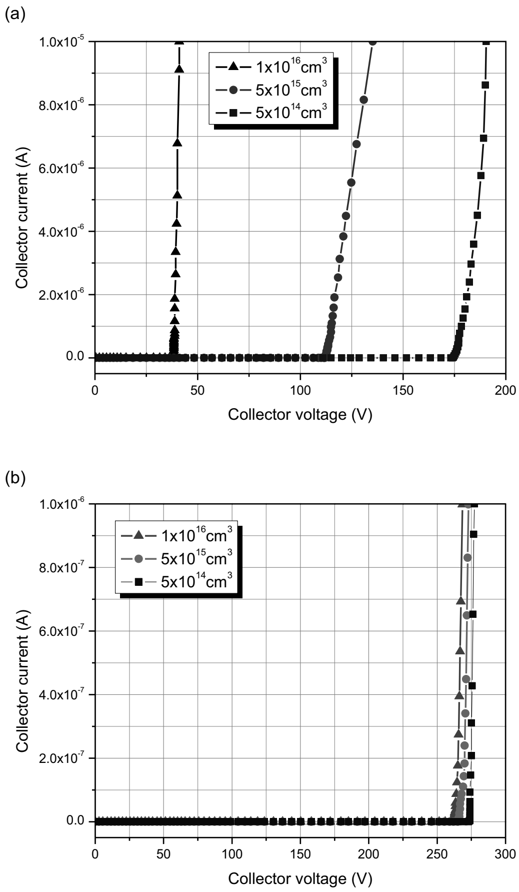

Figure 3. Blocking characteristics of Si/SiC heterojunction optically controlled transistor for different collector region doping concentration (a) without charge compensation layer (b) with charge compensation layer.

From the simulation results, the spectral response of the optically controlled transistor under 5V bias voltage with and without charge compensation layer are shown in figure 4. The device with charge compensation layer has higher spectral response than the device without charge compensation layer. With charge compensation layer, the peak value of optically controlled transistor's spectral response is improved to 130A/W at the wavelength of 550nm. As silicon is used as light absorption material, the response range contains almost all range of the visible spectrum, which is from 400nm to 1100nm.

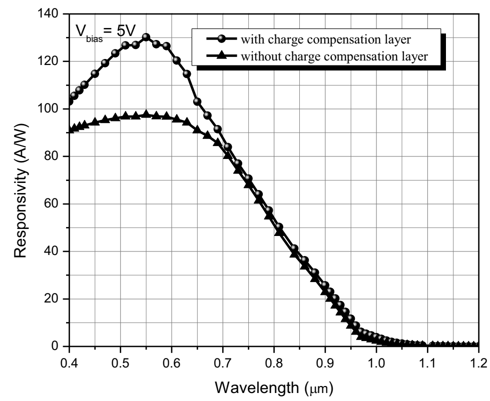

Figure 4. Calculated spectral response of Si/SiC heterojunction optically controlled transistors both with and without charge compensation layer.

Spectral responsivity depends on several inherent factors including material refractive index, absorption coefficient, device structure, doping and temperature of operation. Other external factors such as bias voltage and power of incident light also influence the spectral responsivity. Diffusion process is the main transporting mechanism of photon-generated carrier in neutral region. But the drift process in depletion region is the main process for photocurrent. The structure schematic of light absorption layer in the device with charge compensation layer is shown in figure 5. The photon-generated carrier is a function of the incident distance. The number of the photon-generated carrier in vertical direction and horizontal direction can be calculated respectively as

$$G_1 = \int_0^b (1-R)\frac{P}{h\nu}\alpha e^{-\alpha x}dx = (1-R)\frac{P}{h\nu}(1-e^{-\alpha b}) \quad (3)$$

$$G_2 = \int_e^b (1-R)\frac{P}{h\nu}\alpha e^{-\alpha x}dx = (1-R)\frac{P}{h\nu}(1-e^{-\alpha(b-e)}) \quad (4)$$

where P is the incident power, h is the Planck constant, v is the incident frequency, α is the absorption coefficient of material and R is the reflectivity. The responsivity of the device with 2D electric field in drift region can be write as

$$R = \frac{\beta I}{P_{in}} = \frac{\beta q}{P_{in}}\int_\lambda \left[c\int_0^b \alpha e^{-\alpha x}dx + (d-c)\int_e^b \alpha e^{-\alpha x}dx \right] d\lambda \quad (5)$$

where β is the gain of the transistor. The responsivity of the device with one-dimensional electric field in drift region is

$$R = \frac{\beta I}{P_{in}} = \frac{\beta q}{P_{in}}\int_\lambda \left[c\int_0^b \alpha e^{-\alpha x}dx \right] d\lambda \quad (6)$$

The responsivity of the device with a 2D electric field in drift region is higher than the device with a one-dimensional electric field in drift region obviously. The reason is that the two-dimensional electric field formed

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by charge compensation layer in the transistor can help create one more light absorption layer in horizontal direction. The light absorption layer in horizontal direction improves the spectral response of the optically controlled transistor.

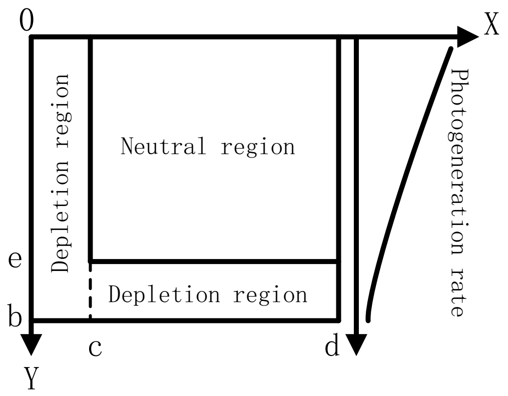

Figure 5. Structure schematic of light absorption layer.

To demonstrate the turn-on characteristics of device with charge compensation layer, the I-V characteristic curve of the device is simulated. The wavelength of incident light is 550nm and the light power density is changed from 0W/cm^2 to 1W/cm^2. The optical characteristics of 4H-SiC/Si heterojunction optically controlled transistor with charge compensation layer for different incident light power density are shown in figure 6. When the power density of the incident light is 0W/cm^2, the device is in blocking state. The device could not be triggered on, unless the power density of the incident light was larger than critical value. The photo current in the device triggered by the light is different, when the power density increased. The light with higher power density can trigger higher photo current, which can support higher base current. As the gain of the transistor is a constant value, increasing the photo current is the only way to obtain higher collector current.

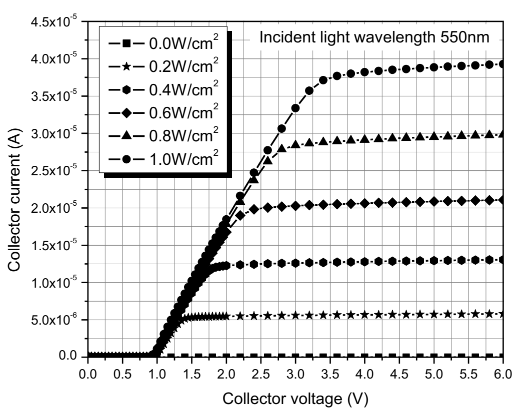

Figure 6. Optical characteristics of Si/SiC heterojunction optically controlled transistor with charge compensation layer for different incident light power density.

Figure 7 shows the transient characteristic of the SiC/Si heterojunction optically controlled transistor with charge compensation layer. As shown in figure 6, the on-state current density is about 160A/cm^2 and the off-state current density is below 0.01A/cm^2. The rising time is about 0.54μs and the falling time is about 0.66μs, which indicates a good transient characteristic of the device under the triggering by a 550nm light.

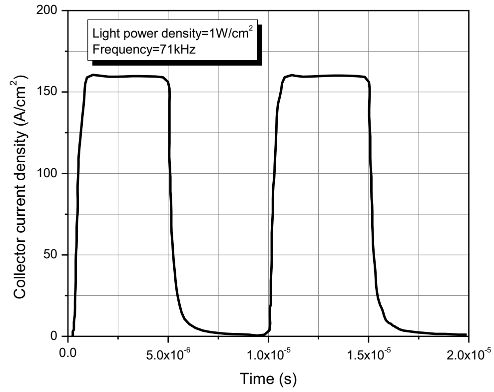

Figure 7. Transient characteristic of the Si/SiC heterojunction optically controlled transistor with charge compensation layer.

4 Conclusion

The optically controlled transistor with charge compensation layer based on 4H-SiC/Si/Si hetero-structure has wide enough spectral response range and big enough spectral response intensity to visible light. The charge compensation layer helps improve the breakdown voltage and spectral responsivity of the optical transistor obviously. The peak value of the spectral response is 130A/W at the wavelength of 550nm. The excellent optical and electrical performance of Si/SiC heterojunction optically controlled transistor makes it attractive for SiC-based optically controlled power devices' development.

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