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SiCGe/SiC heterojunction and its MEDICI simulation of optoelectronic characteristics*

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Optoelectronic characteristics of the $SiC_{1-x}Ge_x$ /SiC heterojunction photodiode are simulated using MEDICI after the theoretical investigation of key properties for $SiC_{1-x}Ge_x$. The calculations show that $SiC_{1-x}Ge_x$ /SiC with x=0.3 may have a small lattice mismatch with 3C-SiC and a good response to the visible light and the near infrared light. The response spectrum of the $SiC_{1-x}Ge_x$ /SiC heterojunction photodiode, which consists of a p-type $SiC_{1-x}Ge_x$ absorption layer with a doping concentration of $1\times10^{15}cm^{-3}$, a thickness of 1.6μm and x=0.3, has a peak of 250mA/W at 0.52μm and the peak can even reach 102mA/W at 0.7μm.

Keywords: SiCGe/SiC, heterojunction, absorption coefficient
PACC: 7865P, 7360P, 7340L, 7110

1. Introduction

Due to its wide bandgap, high breakdown field, and high thermal conductivity, silicon carbide (SiC) can allow electronic devices made from SiC to have a remarkable reduction in on-resistance and a very high operation frequency compared to the devices commonly made from semiconductor silicon. These advantages in material properties also make the SiC device operation temperature reach about 600°C. As a consequence, SiC is a much better material for manufacturing devices applied in the fields of power electronics, high-temperature electronics, and microwave communication. High-temperature feature and chemical inertness of this material also offer advantages to smart sensors with integrated signal conditioning working in a harsh environment. However, it does not offer any advantage to opto-electronics because it is transparent to both the visible and infrared light.

There is an increasing requirement for light-activated SiC power switches and other photo-electronic devices in anti-electromagnetic-interference (EMI) applications.[1] However, SiC is not sensitive to most of the visible lights and all infrared lights, which essentially sets a limit to its application in these ranges. As we proposed earlier,[2] a promising way to solve this problem is to adopt a SiCGe/SiC heterojunction structure, in which the ternary alloy SiCGe with appropriate composition is used as a light-absorption layer. In comparison to either SiGe/Si or SiCGe(SiGeC)/Si heterojunction, however, few studies on the SiCGe/SiC heterojunction structure have been made up to now, although a research group at the University of Delaware has reported on an application of Si–C–Ge alloy in SiC heterostructure bipolar transistors (HBT),[3] which seems to be the only work currently on the Si–C–Ge ternary alloys used to fabricate SiC HBT. However, Ge content in their Si–C–Ge ternary alloy is only a few percent, which may not be sufficient to reduce the band-gap to meet the needs of application in the visible and the infrared regions. Feasibility of applying SiCGe alloys with higher Ge content was confirmed only by fabricating SiGeC/Si infra-red photodetectors with response in a wavelength range of 1.3–1.55μm before.[4]

In order to support the development of a light-activated SiC Darlington transistor with a SiCGe base layer mentioned above, we theoretically investigate the lattice mismatch between SiC and SiCGe and the band-gap modification of the ternary alloys with different composition in a range of higher Ge content. Employing a two-dimensional device simula-

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tor MEDICI, we simulate the optoelectronic characteristics of the SiCGe/SiC heterojunction. Response spectra of the SiCGe/SiC heterojunction structures are also discussed here under different content ratios, doping concentrations and thickness of the light-absorption layer. It is predicted that a SiCGe/SiC heterojunction photo-diode device with properly designed parameters can really output a photocurrent high enough to drive the SiC Darlington transistor proposed in the earlier work.

2. Junction structure

The key points to be considered for constructing a SiCGe/SiC heterojunction are the lattice mismatch between SiCGe and SiC and the absorption coefficient of SiCGe layer. Using the McFarlane–Roberts equation of absorption coefficient for indirect band-gap semiconductors,[5] we calculate the absorption spectra of the $SiC_{1-x}Ge_x$ with different content ratios x at room temperature. Here, we suppose that the SiCGe ternary alloy is composed of SiC and Ge for simplicity. The calculations are shown in Fig.1 with content ratios of 0.1, 0.2, 0.3, 0.4 and 0.5. The corresponding band-gap values are 1.82eV, 1.67eV, 1.52eV, 1.38eV and 1.26eV, while the lattice constants of the $SiC_{1-x}Ge_x$ alloys are 0.44825nm, 0.46131nm, 0.47437nm, 0.48742nm and 0.50048nm, respectively. The detailed calculation was published elsewhere.[6] The calculations show that the response to either the visible or the infra-red light and the lattice match to SiC have a contrary requirement for the content ratio x of the $SiC_{1-x}Ge_x$ alloys. Therefore a compromise has to be made in practice. Among the SiC polytypes, 3C-SiC has a less lattice mismatch to the $SiC_{1-x}Ge_x$ alloys with x being a value of 30% or less, which is high enough to have a required responsibility for triggering light in common use.

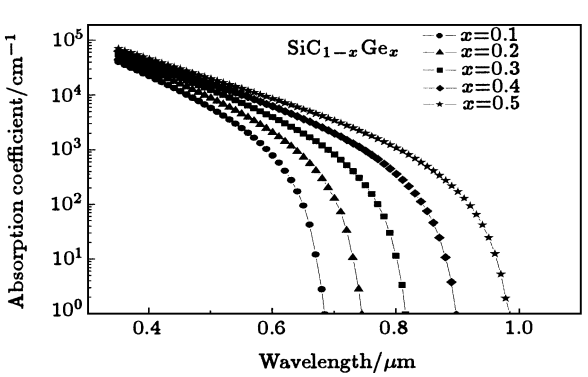


Fig.1. Absorption coefficient spectra of the $SiC_{1-x}Ge_x$ with different Ge content ratios x.

For the purpose of triggering the light-activated Darlington transistor, we design a $SiC_{1-x}Ge_x$/SiC heterojunction as shown in Fig.2. In order to reduce the lattice mismatch between $SiC_{1-x}Ge_x$ layer and the 4H-SiC from which the light-activated Darlington transistor is to be made, we insert an n-type 3C-SiC buffer thin layer between the 4H-SiC substrate and the $SiC_{1-x}Ge_x$ light absorption layer. Doping concentration and thickness of the 3C-SiC buffer layer are temporarily initialized to be 1×10^{15}cm^{-3} and 0.4μm, respectively. In the simulation, content ratio, doping concentration, and thickness of the $SiC_{1-x}Ge_x$ p-type epi-layer are varied in the ranges from 0.1 to 0.5, from 1×10^{14} to 1×10^{18}cm^{-3}, and from 0.6 to 1.6μm, respectively. A triggering light is designed to enter the device from the substrate side because it is transparent and the topside is an opaque metal contact.

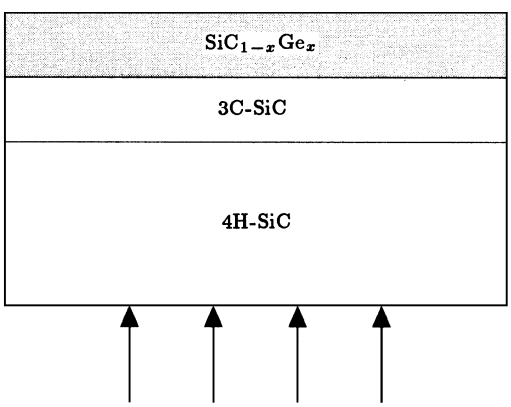


Fig.2. Structure of the $SiC_{1-x}Ge$/SiC heterojunction.

3. Simulation results and analysis

Since the investigation of $SiC_{1-x}Ge_x$ alloys is still at primary stage, the experimental data necessary for simulation are almost unavailable. Therefore, we have to assume that the $SiC_{1-x}Ge_x$ alloy with an appropriate ratio x has SiC-like properties except band gap and photo absorption. The other simulation models employed are the same as those used for SiC in Refs.[7], [8] and [9].

A plot of photocurrent versus incident light intensity under 3V biased is shown in Fig.3 for a $SiC_{1-x}Ge_x$/SiC heterojunction with 0.8 μm in thickness, 1×10^{15} cm^{-3} in doping concentration and x=0.3 in $SiC_{1-x}Ge_x$ layer. The wavelength of the incident light is 0.48 μm. Figure 3 indicates that the photocurrent is a linear function of the incident light intensity. The slope of the plot, i.e. the optoelectronic efficiency, is 224 mA/W. According to our earlier work,[10] the

photocurrent required to trigger the Darlington transistor is at least 1×10^{-4}A/cm^{-2}, and the corresponding incident light intensity is only 0.44mW/cm^{-2} from Fig.3.

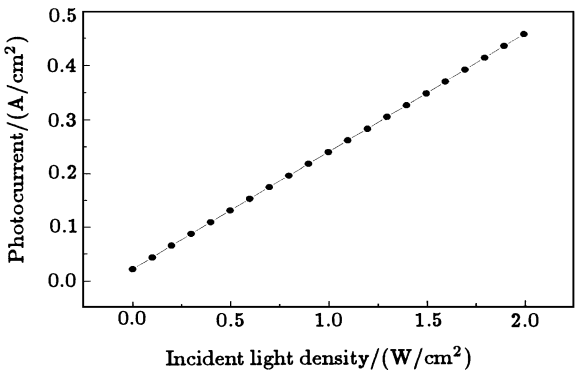


Fig.3. Photocurrent of the $SiC_{1-x}Ge$/SiC heterojunction vs incident light density.

The I–V characteristic curve of the same heterojunction with an incident light intensity of 0.8W/cm^2 is shown in Fig.4. The saturation phenomenon is explained as a sweep-out effect.[11] Apparently, the results are not optimized, and the optimization of the heterojunction parameters will be described below. In the following description, the biased voltage used in the simulation is 3V unless otherwise mentioned.

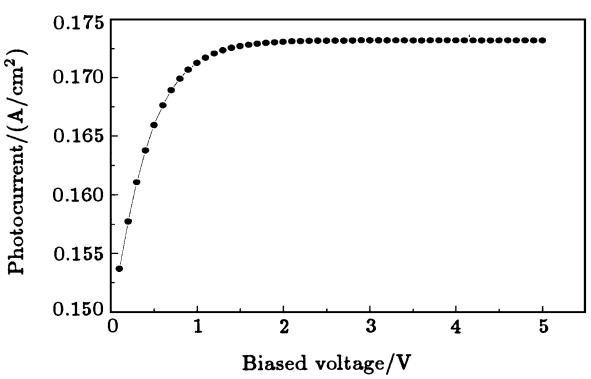


Fig.4. I-V characteristic curve of the $SiC_{1-x}Ge_x$/SiC heterojunction.

The response spectra of the $SiC_{1-x}Ge_x$ /SiC heterojunction are shown in Fig.5 for the content ratios x ranging from 0.1 to 0.5. With the increase of Ge content ratio x in $SiC_{1-x}Ge_x$ alloys, the band-gap width decreases, which results in higher values of the absorption coefficient and the red-shift of the absorption edge in the absorption spectra. Naturally, the peaks of response spectra are elevated and shift towards the red side as the Ge content ratio x increases. In Fig.5, we can observe that the $SiC_{1-x}Ge_x$/SiC (x=0.3) heterojunction has a peak of 224mA/W for the incident light with a wavelength of 0.48μm and the peak can even reach 44.5mA/W when the wavelength of incident light is 0.7μm.

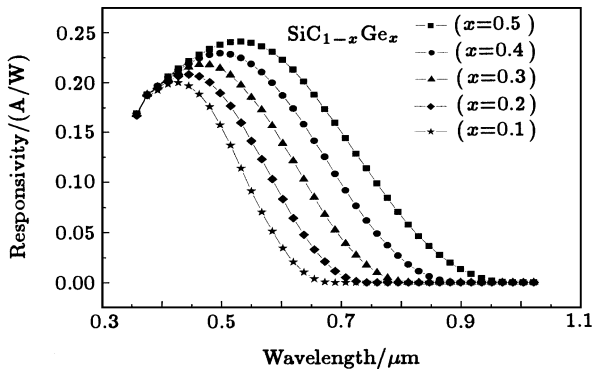


Fig.5. Response spectra of the $SiC_{1-x}Ge_x$/SiC heterojunction with different Ge content ratios x.

Relationship between the light responsivity and the doping concentration in the $SiC_{1-x}Ge_x$ layer is shown in Fig.6. The responsivity increases and the response spectra have red-shifts, as the doping concentration of the $SiC_{1-x}Ge_x$ layer decreases, which is due to the fact that the depletion layer expands and the draw-out effect of internalized field in the depletion region is enhanced as the doping concentration decreases. According to this result, a doping concentration as low as possible is preferred, but considering the difficulty in lowering the doping, a doping concentration should be chosen to be 1×10^{15}cm^{-3} in the $SiC_{1-x}Ge_x$ layer.

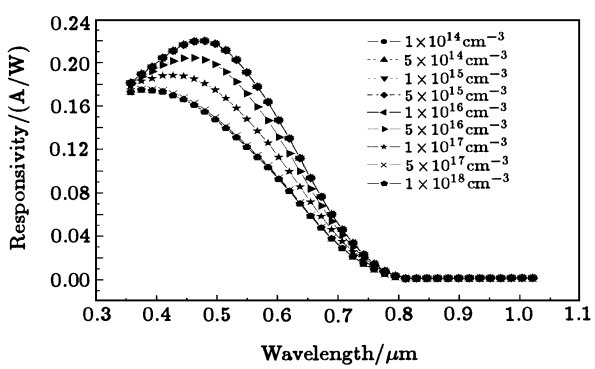


Fig.6. Response spectra of the $SiC_{1-x}Ge_x$/SiC heterojunction with different doping concentrations in $SiC_{1-x}Ge_x$ layer.

The response spectra of the $SiC_{1-x}Ge_x$ /SiC heterojunction with different absorption layer thickness are shown in Fig.7. Within a range of the layer thickness, which depends on the extension of the depletion layer and the diffusion length of minority carrier

in $SiC_{1-x}Ge_x$ layer, the response is a function of the $SiC_{1-x}Ge_x$ layer thickness. From Fig.7, we can find a specific thickness of 1.6μm, beyond which the thickness of $SiC_{1-x}Ge_x$ layer has little effect on photocurrent.

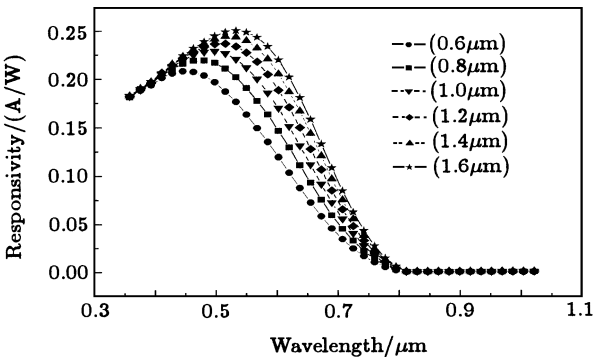


Fig.7. Response spectra of the $SiC_{1-x}Ge_x$/SiC heterojunction with different thickness of the $SiC_{1-x}Ge_x$ layer.

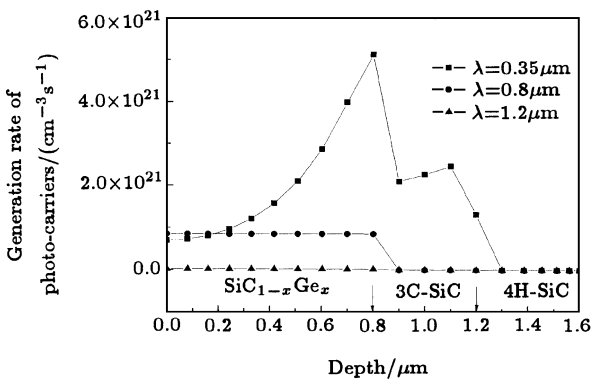


Fig.8. Profiles of photo-carrier generating rate in the $SiC_{1-x}Ge_x$/SiC heterojunction for different wavelengths of incident light.

The photocurrent is produced mainly in $SiC_{1-x}Ge_x$ layer, which can be seen from Fig.8 where profiles of the photo-carrier generating rate are shown for different incident lights. It is shown that both 4H-SiC substrate and 3C-SiC buffer layer have little effect on the photocurrent and response spectra when the wavelength of incident light is longer than 0.4μm. That means that the thickness and the doping concentration of 4H-SiC layer need to be considered only for the Darlington transistor, whereas the thickness and the doping concentration for 3C-SiC layer may be more freely chosen.

Based on the analysis above, a finally designed $SiC_{1-x}Ge_x$ /SiC heterojunction is composed of a p-type $SiC_{1-x}Ge_x$ layer with a thickness of 1.6μm and a doping concentration of $1\times10^{15}cm^{-3}$, an n-type 3C-SiC buffer layer with a thickness of 0.4μm and doping concentration of $1\times10^{15}cm^{-3}$, and an n-type 4H-SiC substrate shared with the Darlington transistor.

4. Conclusion

The $SiC_{1-x}Ge_x$/SiC Heterojunction with x=0.3 may have small lattice mismatch with 3C-SiC and good enough absorption response to the visible and the near infrared lights. The response spectrum of the $SiC_{1-x}Ge_x$/SiC heterojunction photodiodes which consist of a p-type $SiC_{1-x}Ge_x$ absorption layer with a doping concentration of $1\times10^{15}cm^{-3}$, a thickness of 1.6μm and x=0.3 has a peak of 250mA/W at 0.52μm and the peak can even reach 102mA/W at 0.7μm. The heterojunction photodiode can supply a high enough photocurrent to trigger the 4H-SiC Darlington transistor.

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