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Photoelectric Characteristics of $SiC_{1-x}Ge_x$/SiC Heterojunction Diode*

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Abstract Photoelectric characteristics of $SiC_{1-x}Ge_x$/SiC heterojunction diode were simulated using MEDICI tools, and the simulation results are presented and discussed in this letter. The abrupt heterojunction diode is composed of a 1 μm thick heavily doped n-type SiC layer and a 0.4 μm thick lightly doped p-type $SiC_{1-x}Ge_x$ layer with varied composition ratios. It has been shown that photocurrent of the p^-n^+ $SiC_{1-x}Ge_x$/SiC diode is not decreased apparently by change the composition ratio from 0.2 to 0.3 for the applied reverse-bias voltage of 3 V and the incident light intensity of 0.23 W/cm^2. Corresponding photocurrents of the diodes are 7.765×10^{-7} A/μm and 7.438×10^{-7} A/μm, and the longest wavelength limits are 0.64 μm and 0.70 μm, respectively. It has also been shown by the simulation results that p-i-n structure composed by adding a p^+-$SiC_{1-x}Ge_x$ thin layer on top of the lightly doped p-type $SiC_{1-x}Ge_x$ layer is much better for obtaining a higher photocurrent. Under the same conditions, photocurrents of 1.6734×10^{-6} A/μm and 1.844×10^{-6} A/μm can be obtained in the p-i-n $SiC_{1-x}Ge_x$/SiC diodes with $x = 0.2$ and 0.3, respectively.

Keywords $SiC_{1-x}Ge_x$/SiC; Heterojunction; Absorption coefficient

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0 Introduction

There is an increasing requirement of 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 light and all the infrared, which limits the application of SiC to the anti-EMI and opto-electronics areas. There is a promising way in solving this problem. That is to adopt the heterojunction structure, in which the light activated part is fabricated from a material with narrower band-gap. The best material for this application is $SiC_{1-x}Ge_x$ which. Katulka et al[2]. have fabricated $SiC_{1-x}Ge_x$ material using the ion implantation of Ge into SiC and then studied on the electrical characteristics of $SiC_{1-x}Ge_x$/SiC. However, content of Ge in this $SiC_{1-x}Ge_x$ is only 2.3% because of the approach limitation. Such a low content of Ge may be not enough to reduce the band-gap of $SiC_{1-x}Ge_x$ to meet the needs of application in visible and infrared range. If other approaches are adopted, the rich-Ge $SiC_{1-x}Ge_x$ may be fabricated, such as CVD ways. It is very important to study on the light-responsibility of $SiC_{1-x}Ge_x$ with varied composition ratio x and the photoelectric properties of the corresponding $SiC_{1-x}Ge_x$/SiC heterojuction.

In this letter, we present our recent work on $SiC_{1-x}Ge_x$ materials with higher ratio x and the corresponding $SiC_{1-x}Ge_x$/SiC heterojunction diodes. Employing a two-dimensional device simulation simulator MEDICI, we have simulated the photo-electronic characteristics of both p^-n^+ and p-i-n $SiC_{1-x}Ge_x$ heterojunction diodes. The simulation results indicate that both p-i-n $SiC_{0.8}Ge_{0.2}$/SiC and p-i-n $SiC_{0.7}Ge_{0.3}$/SiC are sensitive to the visible light in long-wavelength range, but the sensitive scope of the p^-n^+ $SiC_{0.7}Ge_{0.3}$/SiC and p-i-n $SiC_{0.7}Ge_{0.3}$/SiC structures is more close to the infrared wavelength. It is predicted that SiC devices can be controlled by a triggering light usually employed if $SiC_{1-x}Ge_x$/SiC heterojunction can be successfully adopted.

1 Theoretical analyses

First of all, using McFarlane-Roberts absorption coefficient equations for indirect band-gap semiconductors[3], we have theoretically calculated absorption spectra of the $SiC_{1-x}Ge_x$ at room temperature for different composition ratio x. According to the equations, the absorption coefficient α is only a function of photon energy $h\nu$ when band-gap E_g, phonon energy E_p and constant A are given. Both Ge and SiC are indirect band-gap semiconductors in which the variation trends of absorption coefficients are very similar to each other. Their absorption coefficients increase abruptly as photon energy $h\nu$ is a little larger than the band-gap E_g, and then change with a little increment if $h\nu$ is continuously enlarged[4,5]. We can therefore suppose that the variation trend of absorption coefficients in $SiC_{1-x}Ge_x$ ought to be similar to those of

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SiC and Ge. A band-gap model of the ternary Si-Ge-C alloys has been theoretically established by Orner et al. for varied compositions[6]. Therefore, the band-gap widths of $SiC_{1-x}Ge_x$ alloys can be calculated. It can be obtained that corresponding to the varied composition ratio values of 0.1, 0.2, 0.3, 0.4 and 0.5, the band-gaps of $SiC_{1-x}Ge_x$ alloys are 1.82 eV, 1.67 eV, 1.52 eV, 1.38 eV and 1.26 eV, respectively. We can make out the absorption coefficient of $SiC_{1-x}Ge_x$ resembling those of Ge and SiC by optimizing E_P and A. Thus, we can calculate the absorption spectra of $SiC_{1-x}Ge_x$ for different composition ratio x, as shown in Fig. 1. According to Vegard law, corresponding to the varied composition ratio values of 0.1, 0.2, 0.3, 0.4 and 0.5, the lattice constants of $SiC_{1-x}Ge_x$ alloys are 0.44825 nm, 0.46131 nm, 0.47437 nm, 0.48742 nm and 0.50048 nm respectively, and lattice mismatches between $SiC_{1-x}Ge_x$ alloys and 3C-SiC are 3.0%, 6.0%, 9.0%, 12.0% and 15%, respectively. Considering favorite $SiC_{1-x}Ge_x$ alloys with narrow band-gap and small lattice mismatch with 3C-SiC, we choose $SiC_{0.8}Ge_{0.2}$ and $SiC_{0.7}Ge_{0.3}$ as our investigation objects here.

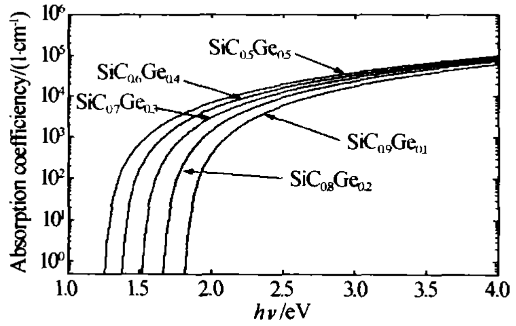

Fig. 1 Absorption coefficient spectra of $SiC_{1-x}Ge_x$ for varied composition ratio x

2 Computer simulation

The structure of pn^+ $SiC_{1-x}Ge/SiC$ diode is shown in Fig. 2, where the doping concentration of 1 μm thick n-type 3C-SiC is designed to be 4×10^{18} cm^{-3} and the doping concentration of 0.4 μm thick p-type $SiC_{1-x}Ge_x$ is designed to be 4×10^{15} cm^{-3}. Then the depletion region is formed in $SiC_{1-x}Ge_x$. The normal incident triggering light with stable light intensity of 0.23 W/cm^2 is from below the SiC layer. If the photon energy $h\nu$ of incident light is smaller than the band-gap of SiC and bigger than the band-gap of $SiC_{1-x}Ge_x$, the incident light will transmit the SiC layer and be absorbed by the $SiC_{1-x}Ge_x$ layer where a lot of photogenerated carriers can be produced. The photogenerated holes drift to upper surface of the depletion region and the photogenerated electrons drift in the opposite direction with the effect of the internalized electric field of depletion region. Then there is the photocurrent through the device with the reverse-bias voltage.

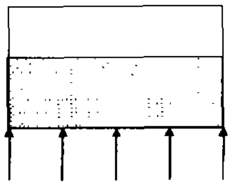

Fig. 2 Structure of pn^+ SiCGe/SiC

It is shown in Fig. 3 to photocurrent spectra of p^-n^+ $SiC_{0.8}Ge_{0.2}/SiC$ diodes under different reverse-bias voltages and the same incident light intensity of 0.23 W/cm^2. In Fig. 3, we can observe that the photocurrent is very small when V_R is 1 V, it's clear to observe the photocurrent changing with the varied λ, the photocurrent is the largest under the effect of the same wavelength in these three reverse-bias voltages and the photocurrent changing trend with λ is also the most obvious. So the increasing reverse-bias voltage enhances the photocurrent with the same intensity of incident light. The photocurrent decreases sharply when wavelength λ is larger than 0.64 μm with reverse-bias voltage of 3 V, because of the absorption coefficient of $SiC_{0.8}Ge_{0.2}$ decreasing sharply. When wavelength of incident light is 0.64 μm, the photocurrent of p^-n^+ $SiC_{0.8}Ge_{0.2}/SiC$ is 7.765×10^{-7} A/μm. And when λ is 0.7 μm, the photocurrent is very small. When λ is smaller than 0.35 μm, the photocurrent also decreases sharply ascribing to SiC layer absorbing lots of incident light and lack of the photogenerated carriers in $SiC_{1-x}Ge_x$ layer. The photocurrent is negligible with λ of 0.3 μm. Photocurrent spectra of p^-n^+ $SiC_{0.7}Ge_{0.3}/SiC$ diodes under different reverse-bias voltages and the same incident light intensity of 0.23 W/cm^2 is shown in Fig. 4. The photocurrent variation trends of p^-n^+ $SiC_{0.7}Ge_{0.3}/SiC$ is very similar to those of p^-n^+ $SiC_{0.8}Ge_{0.2}/SiC$. It is the difference that p^-n^+ $SiC_{0.7}Ge_{0.3}/SiC$ diode is more sensitive to the incident light of 0.7 μm as

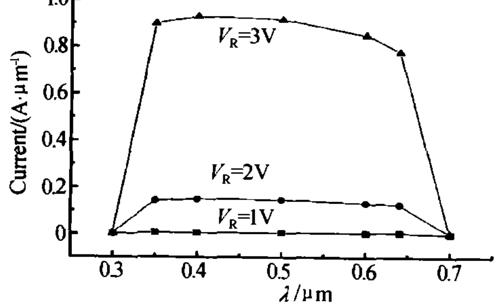

Fig. 3 Photocurrent spectra of p^-n^+ $SiC_{0.8}Ge_{0.2}/SiC$ diodes under different reverse-bias voltages and the same incident light intensity of 0.23 W/cm^2

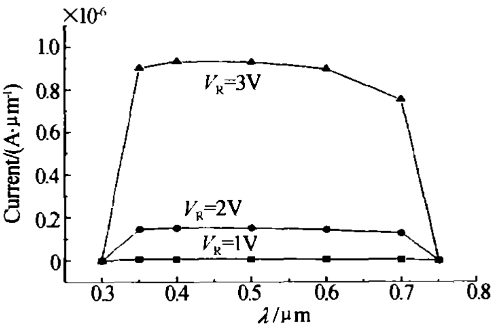

Fig. 4 Photocurrent spectra of $p^- n^+$ $SiC_{0.7}Ge_{0.3}$/SiC diodes under different reverse-bias voltages and the same incident light intensity of 0.23 W/cm^2

compared with $p^- n^+$ $SiC_{0.8}Ge_{0.2}$/SiC and its photocurrent is 7.438×10^{-7} A/μm.

In order to enhance the photocurrent of $SiC_{1-x}Ge_x$/SiC diode, $p^- n^+$ is superseded in favor of p-i-n. And the p-i-n structure is composed by adding a 0.1 μm thick p^+-$SiC_{1-x}Ge_x$ thin layer on top of the lightly doped p-type $SiC_{1-x}Ge_x$ layer in which the doping concentration of $p^- n^+$ $SiC_{1-x}Ge_x$ thin layer is 4×10^{17} cm^{-3}. To reflect the p-i-n superiority, a comparison of the photocurrent spectra of $SiC_{0.8}Ge_{0.2}$/SiC p-i-n and $p^- n^+$ diodes under the same reverse-bias voltage of 3 V and the same incident light intensity of 0.23 W/cm^2 is shown in Fig. 5. We can discover that the photocurrent of p-i-n $SiC_{0.8}Ge_{0.2}$/SiC diode is 1.6734×10^{-6} A/μm with the incident light of 0.64 μm larger than that of $p^- n^+$ $SiC_{0.8}Ge_{0.2}$/SiC diode. Furthermore, a comparison of the photocurrent spectra of $SiC_{0.7}Ge_{0.3}$/SiC p-i-n and $p^- n^+$ diodes under the same reverse-bias voltage of 3 V and the same incident light intensity of 0.23 W/cm^2 is also shown in Fig. 6. It's similarly ready to find that the photocurrent of p-i-n $SiC_{0.7}Ge_{0.3}$/SiC diode is 1.844×10^{-6}A/μm with the incident light of 0.7 μm larger than that of $p^- n^+$ $SiC_{0.7}Ge_{0.3}$/SiC diode. Thus it can be deduced that photocurrent characteristic of p-i-n $SiC_{1-x}Ge_x$/SiC diode is more sensitive to incident light than that of $p^- n^+$ $SiC_{1-x}Ge_x$/SiC diode.

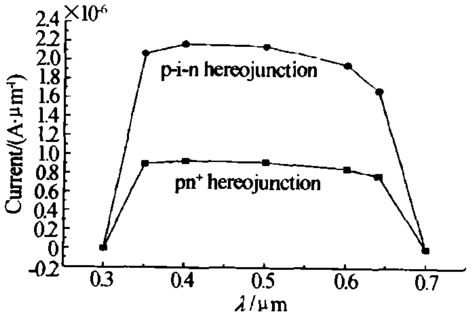

Fig. 5 A comparison of the photocurrent spectra of $SiC_{0.8}Ge_{0.2}$/SiC p-i-n and $p^- n^+$ diodes under the same reverse-bias voltage of 3 V and the same incident light intensity of 0.23 W/cm^2

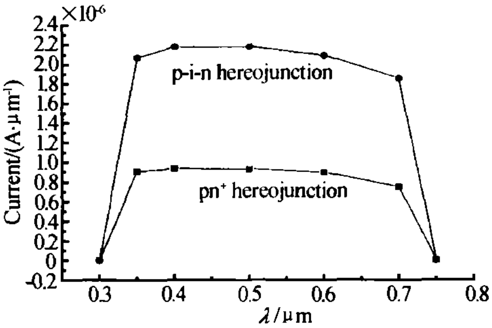

Fig. 6 A comparison of the photocurrent spectra of $SiC_{0.8}Ge_{0.3}$/SiC p-i-n and $p^- n^+$ diodes under the same reverse-bias voltage of 3 V and the same incident light intensity of 0.23 W/cm^2

A comparison of the photocurrent response of incident light intensity of $SiC_{0.8}Ge_{0.2}$/SiC p-i-n diodes under the same incident light wavelength of 0.6 μm and $SiC_{0.7}Ge_{0.3}$/SiC p-i-n diodes under the same incident light wavelength of 0.65 μm are shown in Fig. 7 and Fig. 8, respectively. From Fig. 7 and Fig. 8, we can discover that the incident light intensity is not linear with photocurrent. When the incident light intensity is larger than 0.2 W/cm^2, the photocurrent will become saturation.

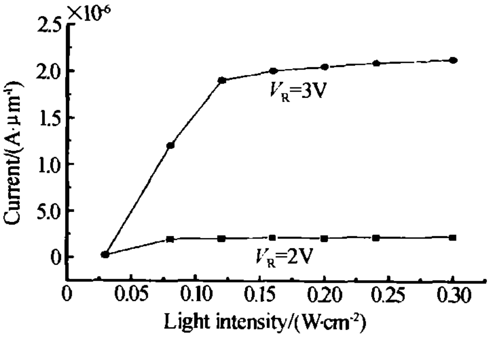

Fig. 7 A comparison of the photocurrent response of incident light intensity of $SiC_{0.8}Ge_{0.2}$/SiC p-i-n diodes under the same incident light wavelength of 0.6 μm

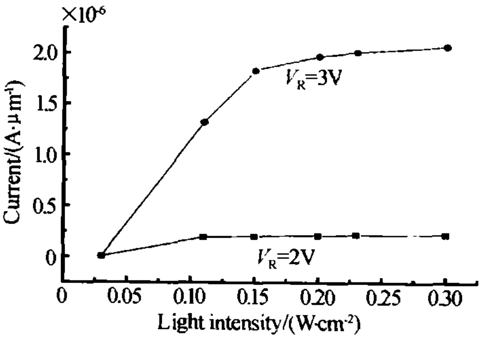

Fig. 8 A comparison of the photocurrent response of incident light intensity of $SiC_{0.7}Ge_{0.3}$/SiC p-i-n diodes under the same incident light wavelength of 0.65 μm

3 Conclusion

In conclusion, $SiC_{0.8}Ge_{0.2}$ and $SiC_{0.7}Ge_{0.3}$ is sensitive to the visible light in long-wavelength range, and the sensitive scope of $SiC_{0.7}Ge_{0.3}$/SiC is close to infrared wavelength. If $p^- n^+$ is superseded in favor of p-i-n, the larger photocurrent can be obtained with the same reverse-bias voltage and the same incident light intensity. So it is predicted that SiC devices can be controlled by a triggering light usually employed by adopting $SiC_{1-x}Ge_x/SiC$ heterojunction.

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$SiC_{1-x}Ge_x$/SiC 异质结光电二极管特性的研究

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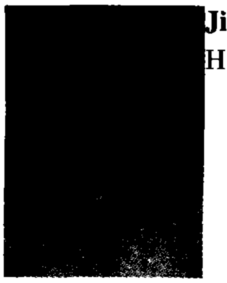
摘 要 使用二维器件模拟软件 Medici，对 $SiC_{1-x}Ge_x/SiC$ 异质结的光电特性进行了模拟．设计了 N 型重掺杂 SiC 层的厚度为 1 μm，P 型轻掺杂 $SiC_{1-x}Ge_x$ 层厚为 0.4 μm，二者之间形成突变异质结．在反向偏压 3 V、光强度为 0.23 W/cm^2 的条件下，p^-n^+ $SiC_{0.8}Ge_{0.2}/SiC$ 和 p^-n^+ $SiC_{0.7}Ge_{0.3}/SiC$ 敏感波长 λ 分别可以达到 0.64 μm 和 0.7 μm，光电流分别为 7.765×10^{-7} A/μm 和 7.438×10^{-7} A/μm；为了进一步提高 $SiC_{1-x}Ge_x/SiC$ 异质结的光电流，我们把 p^-n^+ 两层结构改进为 p-i-n 三层结构．在同样的偏压、光照条件下，p-i-n $SiC_{0.8}Ge_{0.2}/SiC$ 和 p-i-n $SiC_{0.7}Ge_{0.3}/SiC$ 的光电流分别达到 1.6734×10^{-6} A/μm 和 1.844×10^{-6} A/μm．

关键词 $SiC_{1-x}Ge_x$；异质结；吸收系数



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