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A Novel Ideal Ohmic Contact SiGeC/Si Power Diode with Graded Doping Concentration*

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Abstract: A novel structure of ideal ohmic contact p^+ (SiGeC)-n^--n^+ diodes with three-step graded doping concentration in the base region is presented, and the changing doping concentration gradient is also optimized. Using MEDICI, the physical parameter models applicable for SiGeC/Si heterojunction power diodes are given. The simulation results indicate that the diodes with graded doping concentration in the base region not only have the merit of fast and soft reverse recovery but also double reverse blocking voltage, and their forward conducting voltage has dropped to some extent, compared to the diodes with constant doping concentration in the base region. The new structure achieves a good trade-off in Q_s-V_f-I_r, and its combination of properties is superior to ideal ohmic contact diodes and conventional diodes.

Key words: SiGeC/Si heterojunction; power diodes; reverse blocking voltage; ohmic contact

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1 Introduction

Conventional Si p-i-n diodes cannot realize a good trade-off in stored charge (Q_s), forward voltage (V_f), and reverse leakage (I_r)[1] because of the limitation of silicon material. In order to meet the demands of high frequency power electronic circuits for power diodes with low forward voltage, high breakdown voltage, low reverse leakage current, and soft recovery characteristics, new semiconductor materials have been applied to the improvement of performance of power diodes, and several novel p^+ (SiGe)-n^--n^+ and p^+ (SiGeC)-n^--n^+ heterojunction power diodes have been given by our research group[2]. New device structures have also been introduced. For example, our research group has proposed an ideal ohmic contact power diode to improve the reverse recovery characteristics of the device[3], but at the cost of reverse breakdown voltage and forward characteristics. For improving the characteristics of ideal ohmic contact diodes, a novel ideal ohmic contact p^+(SiGeC)-n^--n^+ power diode with three-step graded doping concentration in the base region is presented in this paper.

The new structure is achieved by introducing a three-step graded doping concentration in the base region of ideal ohmic contact diodes, which reduces the negative effect of the p^+ region in the vicinity of the cathode on the forward characteristic and reverse breakdown characteristic. Compared to ideal ohmic contact diodes, the new structure not only has the merit of fast and soft reverse recovery, but also doubles the reverse blocking voltage. And its forward conducting voltage has dropped to some extent. Thus the new ideal ohmic contact p^+ (SiGeC)-n^--n^+ heterojunction power diodes achieve a good trade-off in Q_s-V_f-I_r.

2 Device structure and process

The new structure, shown in Fig. 1(a), is achieved by introducing a three-step graded doping concentration in the base region of the ideal ohmic contact diode whose structure is shown in Fig. 1 (b). The doping concentration in the base of the

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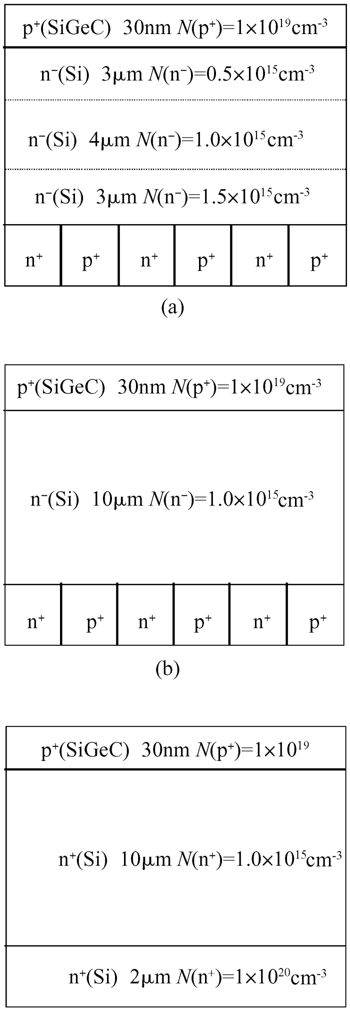
ideal ohmic contact diodes is $1.0\times10^{15}cm^{-3}$, and the three-step graded doping concentration (N_1-N_2-N_3) increases in the base region from the p^+ boundary to the n^+ boundary. The structure of conventional p^+(SiGeC)-n^--n^+ heterojunction power diodes is also given in Fig.1(c).



(a)

(b)

(c)

Fig.1 Comparison of three kinds of p^+(SiGeC)-n^--n^+ heterojunction power diodes (a) Ideal ohmic contact diode with three-step graded doping concentration in n^- region; (b) Ideal ohmic contact diode; (c) Conventional diode

The structure of conventional p^+(SiGeC)-n^--n^+ diodes is similar to that of p^+(SiGe)-n^--n^+ diodes except that the p^+(SiGeC) layer thickness in the former diodes has more flexibility, which can be changed from tens of nanometers to hundreds of nanometers, while the p^+(SiGe) layer thickness in the latter diodes must be less than 50nm. The reason is that the 4.2% lattice mismatch between Si and Ge imposes several restrictions on the device's structure, limiting the application only to low Ge fractions, thin active layers, and relatively lower process temperature windows. By incorporating smaller-sized carbon atoms substitutionally into a SiGe system, it becomes possible to reduce the strain within the SiGeC system and to increase the critical thickness.

Ideal ohmic contact p^+(SiGeC)-n^--n^+ diodes are achieved by using a "universal contact", which has an alternate p^+-n^+ mosaic layer on a cathode interface and acts as an ideal ohmic contact for electrons and holes simultaneously, while the n^--n^+ interface of the conventional ohmic contact diodes forms an ohmic contact just for majority carriers (electrons in this case). This contact allows the transport of electrons across the interface, and an electric field is created due to the carrier concentration gradient. Owing to the influence of the electric field, the minority carriers (holes in this case) approaching the interface turn back from the interface. Therefore, the conventional ohmic contact cannot achieve fast turn-off because the carriers would be trapped in the n^- region, while the ideal ohmic contact can remarkably decrease the reverse recovery time and the leakage current. Unfortunately, the ideal ohmic contact diodes can improve the reverse recovery characteristic, but only at the sacrifice of reverse breakdown voltage and forward conduction characteristics. For forward bias, the n^--p^+ junction at the cathode is on the reverse bias, which reduces the conduction modulation effect and induces the deterioration of the forward conduction characteristic. For reverse bias, the existence of the p^+ region at the cathode is equivalent to introducing a parasitic pnp transistor, which reduces the reverse blocking voltage of the devices remarkably.

The new structure improves the reverse blocking and forward conduction characteristics using the built-in field resulting from the graded concentration in the n^- region. Furthermore, the improvement of the novel type of diodes is achieved by adding carbon atoms to the SiGe system, which was presented in Ref.[4]. In theory, the strain within the SiGeC alloys system can be compensated completely by altering the Ge/C ratio. Actually, it is impossible to make all the carbon atoms go into the substitution sites for a SiGeC system with carbon content greater than 1%, under all kinds of processing conditions compatible with Si[5,6]. That is, the SiGeC epitaxial layer would be deteriorated quickly due to misfit dislocations, defects, and Si-C precipitates when the carbon content is more than 1%[7]. Thus, the carbon content is strictly limited to 1% in the novel p^+(SiGeC)-n^--n^+ diodes presented in this paper.

The bonding technique is applied to form the diode. The substrate is n-type Si(100) with a doping concentration of $1.0\times10^{15}\,\mathrm{cm}^{-3}$. An n^- silicon epitaxial layer of 3μm ($0.5\times10^{15}\,\mathrm{cm}^{-3}$) is grown, followed by the thin (~30nm) SiGeC layers, in which a heavily doped p^+ region is grown. The SiGeC layers are deposited with an ultrahigh vacuum chemical vapor deposition (UHV/CVD) system to achieve precise control of the Ge, C and B profiles[8]. Subsequently an n^- silicon epitaxial layer of 5μm ($1.5\times10^{15}\,\mathrm{cm}^{-3}$) is grown on another substrate of the same kind. The alternating p^+-n^+ mosaic layer on the cathode interface is formed by selective diffusion. Then the two substrates are bonded to support the required reverse breakdown voltage. The Ti/Au-contacts are identified to be ohmic and to have a linear current-voltage characteristic.

3 Model

In order to achieve realistic results, based on MEDICI, several important physical models applicable for SiGeC/ Si power diodes are given.

3.1 Band gap

The band offsets for SiGeC alloys strained on Si have been calculated by considering hydrostatic strain (ΔE_h) and uniaxial strain (ΔE_a) as well as the intrinsic chemical effect of Ge and C (ΔE_s), which agree well with the available experiment results. The total change in a band is expressed as[9]

$$\Delta E = \Delta E_a + \Delta E_h + \Delta E_s \tag{1}$$

Considering all the contributions, the band offsets for ternary SiGeC alloys with Ge and C contents limited to 50% and 3%, respectively, are finally given by

$$\Delta E_g = \begin{cases} \Delta E_{\Delta 4} - \Delta E_{hh}, & y \leqslant x/8.2 \\ \Delta E_{\Delta 2} - \Delta E_{lh}, & y > x/8.2 \end{cases} \tag{2}$$

$$\Delta E_c = \min(\Delta E_{\Delta 2}, \Delta E_{\Delta 4}) \tag{3}$$

$$\Delta E_v = \max(\Delta E_{lh}, \Delta E_{hh}) \tag{4}$$

where

$$\Delta E_{\Delta 2}(x,y) = 0.67x - (6.5 + 0.6x)y$$

$$\Delta E_{\Delta 4}(x,y) = -(0.89 + 0.94x)y$$

$$\Delta E_{hh}(x,y) = 0.74x - (3.37 + 0.56x)y - (20.9 + 0.18x)y^2$$

$$\Delta E_{lh}(x,y) = P_0(x) + P_1(x)y + P_2(x)y^2 + P_3(x)y^3$$

$$\begin{cases} P_0(x) = 0.46x + 0.4x^2 - 0.4x^3 \\ P_1(x) = -(0.212 + 17.1x + 202.2x^2 + 245.6x^3) \times (1 - 4.6x + 117.5x^2)^{-1} \\ P_2(x) = (26.8 + 2228x - 7349x^2 - 8594x^3) \times (1 + 22.1x - 220.3x^2 + 1241x^3)^{-1} \\ P_3(x) = (-668.7 - 4.04\times10^4 x + 3.2\times10^5 x^2 - 3.75\times10^5 x^3)(1 + 19.8x - 200x^2 + 929x^3)^{-1} \end{cases}$$

3.2 Mobility

The carrier mobility can be expressed as a function of the effective mass m^* and the scattering time τ:

$$\mu = q\tau/m^* \tag{5}$$

The scattering time τ is a parameter that presents all scattering mechanisms at carrier experiences.

$$1/\tau = \sum 1/\tau_i \tag{6}$$

Therefore, the mobility is dominated by the scattering mechanism with the smallest time constant.

On the basis of the analysis mentioned above and the experimental data[10] of Osten *et al.*, we present the expression of carrier mobility as

$$\mu_p = \frac{\mu_{p.max} - \mu_{p.min}}{1 + (N_{total}/N'_0)^{\beta}} + \mu_{p.min} \tag{7}$$

where N_{total} is the doping content, $\mu_{p.min} = 49.7\times(1 + 30x^2 - 17y - 900y^2)\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$, $\beta = 0.7$, $\mu_{p.max} = 480\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$, $N'_0 = 1.61\times10^{17}\,\mathrm{cm}^{-3}$, and

$$\mu_n = \frac{\mu_{n.max} - \mu_{n.min}}{1 + (N_{total}/N_0)^{\alpha}}(1 + a_1 x + a_2 x^2 + a_3 x^3) + \mu_{n.min} \tag{8}$$

where N_{total} is also the doping content, $\alpha = 0.625$, $N_0 = 1.1\times(1 + 14.15x)\times10^{17}\,\mathrm{cm}^{-3}$, $\mu_{n.min} = 175\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$, $a_1 = -3.02$, $a_2 = -7.08$, $a_3 = 53.08$, and $\mu_{n.max} = 1350\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$.

Furthermore, in order to achieve realistic results, some other physical effects, such as bandgap narrowing and high-field saturation, are also considered in the simulation.

4 Simulation results and analysis

As shown in Fig.2, the reverse blocking voltage of the ideal ohmic contact p^+ (SiGeC)-n^--n^+ diodes with three-step graded doping concentration in the base region almost doubles, and their hard breakdown characteristics become more notable, compared to that of the ideal ohmic contact diodes. We know that there is a parasitic pnp transistor in the ideal ohmic contact diodes resulting from the introduction of the ideal ohmic contact structure. Thus the reverse blocking voltage of the ideal ohmic contact diodes is restricted by the original p-i-n diodes and the parasitic pnp transistor, and determined by the latter, whose reverse blocking voltage is lower. The n^- region doping concentration near the cathode p^+-n^- junction in the new structure increases from 1.0×10^{15} to $1.5\times10^{15}\mathrm{cm}^{-3}$, which raises the electron potential of this region. For this, the common-base enlargement factor (α_F) of the pnp transistor decreases. According to Eq.(9), the breakdown vol tage of the transistor increases. Thus, the reverse blocking voltage of the ideal ohmic contact diodes with three-step graded doping concentration in the base region almost doubles compared to that of the ideal ohmic contact diodes.

$$V_{(BR)CE0} = (1-\alpha_F)^{1/k} V_{(BR)CBO} \quad (9)$$

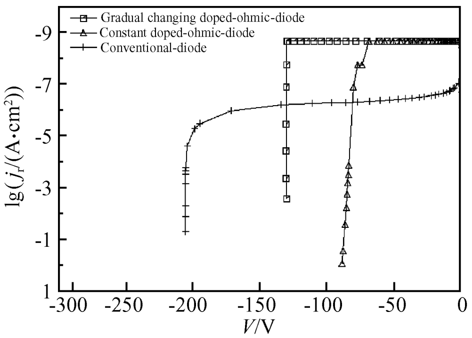


Fig.2 Comparison of the reverse I-V characteristics for three kinds of p^+ (SiGeC)-n^--n^+ heterojunction power diodes

It also can be seen from Fig.2 that the reverse leakage current of the new structure is notably lower than that of the conventional diodes. This is achieved by introducing an alternating p^+-n^+ mosaic layer on the cathode interface. For reverse bias, some holes are injected into the base region from the p^+ region in the cathode, and the generation rate of electron-holes in the space-charge region is reduced by those injected holes. Because of this, the source of the reverse leakage of the new structure is depressed. Therefore, the reverse leakage current of the conventional diodes is higher than that of the new diodes and the ideal ohmic contact diodes.

Figure 3 shows a comparison of the forward I-V characteristics of three kinds of diodes. It can be seen that the forward current density of the new structure increases to some extent, compared to that of the ideal ohmic contact diodes. The reason is that the n^- region doping concentration near the anode p^+-n^- junction of the new structure decreases and the electron potential also falls, which weakens the inhibition of the conduction modulation effect resulting from the introduction of the ideal ohmic contact structure and increases the electronic density of forward conduction. Therefore, the forward current density of the new structure increases to some extent with the introduction of three-step graded doping concentration in the base region.

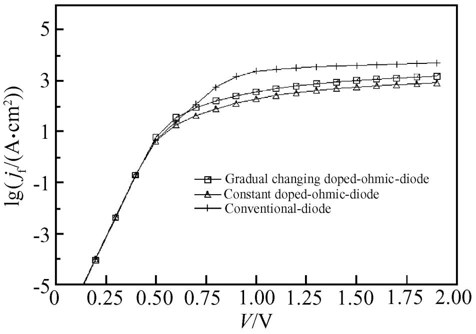


Fig.3 Comparison of the forward I-V characteristics for three kinds of p^+ (SiGeC)-n^--n^+ heterojunction power diodes

The reverse recovery time of the new structure decreases, the soft factor increases, and the reverse recovery peak current also decreases to some extent, as shown in Fig.4, compared to that of the ideal ohmic contact diodes.

For forward bias, a large number of excessive charges are stored in the n^- region because of the conduction modulation effect. For reverse bias, those stored charges will vanish by flowing away

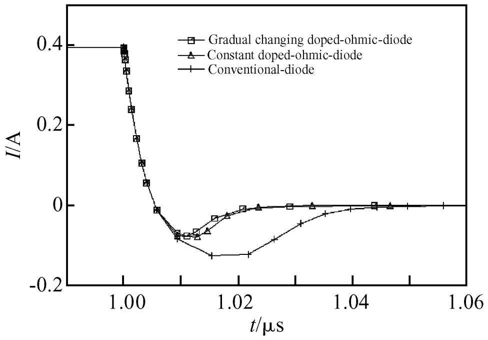


Fig. 4 Comparison of the reverse recovery characteristics for three kinds of p^+ (SiGeC)-n^--n^+ heterojunction power diodes

or recombining in the n^- region. When introducing three-step graded doping concentration in the base region, there will be a built-in field, which speeds the process of carriers swept from the base region. Furthermore, compared to the constant doping diodes, the doping concentration near the p^+-n^- junction at the anode for three-step graded doping diodes is slightly lower, which contributes to the acceleration of the process of the space-charge region's development at the p^+-n^- junction to support a part of the reverse bias voltage. Thus, the storing time t_A is shortened to some extent. On the other hand, there are still relative excessive stored charges in the middle n^- region and near the n^--n^+ junction, which is not swept out rapidly. Therefore, the falling time t_B is almost not affected by the introduction of three-step graded doping concentration, and the novel structure can achieve a faster and softer reverse recovery characteristic.

5 Optimization of concentration gradient in the base region

The concentration gradient in the base region is an important parameter for the novel structure, and it can be optimized to obtain better device characteristics. Take a three-step graded doping concentration in the base region for example: The three-step doping concentration (N_1-N_2-N_3) increases from the p^+ boundary to the n^+ boundary. The graded doping concentrations are $(0.5\sim1.0\sim1.5)\times10^{15}\mathrm{cm}^{-3}$, $(0.2\sim1.0\sim1.5)\times10^{15}\mathrm{cm}^{-3}$, $(0.5\sim1.2\sim1.5)\times10^{15}\mathrm{cm}^{-3}$, $(0.5\sim1.0\sim4.0)\times10^{15}\mathrm{cm}^{-3}$ from the p^+ boundary to the n^+ boundary, respectively.

The reverse blocking voltage of the new structure is sensitive to the concentration gradient in the base region, as shown in Fig. 5. The lower the N_1 region concentration or the higher the N_3 region concentration, the better the reverse blocking characteristics of the new structure is. That is, the greater the concentration gradient in the base region, the higher blocking voltage the new structure has.

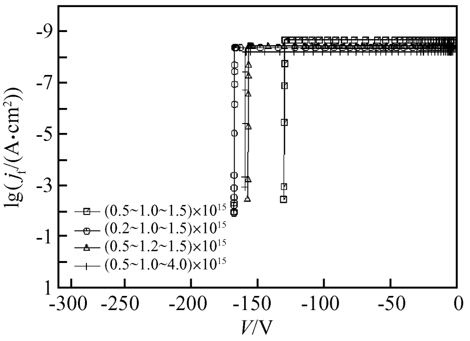


Fig. 5 Comparison of the reverse I-V characteristics for p^+ (SiGeC)-n^--n^+ diodes with different concentration gradients in the base region

It can be seen from Fig. 6 that the forward current density of the new structure improves to some extent, with the increasing of concentration gradient in the base region. Thus the reverse blocking characteristics and the forward I-V characteristics of the new structure are improved when the concentration gradient in the base region is enhanced. However, the reverse recovery characteristic of the new structure, as shown in Fig. 7, is better for a more uniform concentration gradient in the base when the doping concentrations of the N_1 region and N_3 region are confirmed, which in-

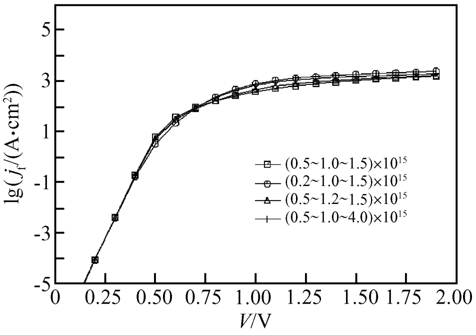


Fig. 6 Comparison of the forward I-V characteristics for p^+ (SiGeC)-n^--n^+ diodes with different concentration gradients in the base region

dicates that a continuous transition of the concentration in the base region from the p^+ boundary to the n^+ boundary is helpful to improve the reverse recovery time of the new structure. It thus can be concluded that the characteristics of the structure is best for a continuous doping gradient in the base region, on the condition that the doping concentration gradient range in the base region from the p^+ boundary to the n^+ boundary is the same. However, in this paper we choose the three-step graded doping concentration in the base region of the new structure, for the purpose of not only improving the characteristics of the structure, but also reducing the processing demand.

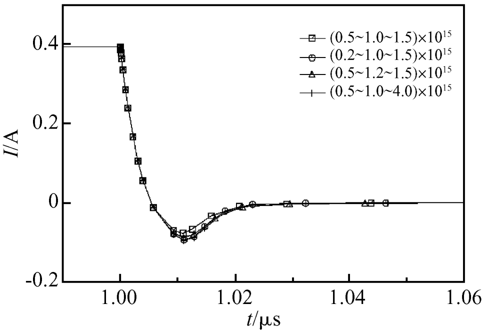


Fig. 7 Comparison of the reverse recovery characteristics for p^+ (SiGeC)-n^--n^+ diodes with different concentration gradients in the base region

6 Conclusion

A novel structure of ideal ohmic contact p^+ (SiGeC)-n^--n^+ diodes with a three-step graded doping concentration in the base region has been presented, and the changing doping concentration gradient has also been optimized. In addition, the physical parameter models applicable for the SiGeC/Si heterojunction power diodes have been given. Based on the analysis of the structure mechanism, the characteristics of the new structure have been explained reasonably. The simulation results indicate that the diodes with graded doping concentration in the base region not only have the merit of fast and soft reverse recovery , but also double the reverse blocking voltage. And their forward conduction voltage have dropped to some extent, compared to that of the ideal ohmic contact diodes. Thus, the new structure achieves a good trade-off in Q_s-V_f-I_r, and its combination of properties is superior to ideal ohmic contact diodes and conventional diodes.

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一种新型渐变掺杂理想欧姆接触 SiGeC/Si 功率二极管*

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摘要： 将新器件结构与新型半导体材料相结合，提出了一种新型的 n^- 区三层渐变掺杂理想欧姆接触型 p^+(SiGeC)-n^--n^+ 异质结功率二极管，并对 n^- 区的杂质分布梯度进行了优化．基于 MEDICI，给出了该结构的关键物理参数模型，并在此基础上对新结构的设计思路和工作原理进行了全面分析．结果表明，与常规理想欧姆接触结构相比，该新结构在保持快而软反向恢复特性的前提下，反向阻断电压增加了近一倍，而且正向通态特性也有所改善，很好地实现了功率二极管中 Q_s-V_f-I_r 三者的良好折中．

关键词： SiGeC/Si 异质结；功率二极管；反向阻断特性；欧姆接触

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