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Research on reverse recovery characteristics of SiGeC p-i-n diodes*

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This paper analyses the reverse recovery characteristics and mechanism of SiGeC p-i-n diodes. Based on the integrated systems engineering (ISE) data, the critical physical models of SiGeC diodes are proposed. Based on heterojunction band gap engineering, the softness factor increases over six times, reverse recovery time is over 30% short and there is a 20% decrease in peak reverse recovery current for SiGeC diodes with 20% of germanium and 0.5% of carbon, compared to Si diodes. Those advantages of SiGeC p-i-n diodes are more obvious at high temperature. Compared to lifetime control, SiGeC technique is more suitable for improving diode properties and the tradeoff between reverse recovery time and forward voltage drop can be easily achieved in SiGeC diodes. Furthermore, the high thermal-stability of SiGeC diodes reduces the costs of further process steps and offers more freedoms to device design.

Keywords: SiGeC, softness factor, thermal-stability, lifetime control
PACC: 7340L

1. Introduction

In the fields of power electronics, there require high power switching devices having the low forward voltage drop and high-speed switching.[1] So far, diodes with the p-i-n structures are used due to their low fabrication cost [2]. One of the biggest subjects in these diodes is reducing the recovery time without increasing the forward voltage drop. To decrease the recovery time, the lifetime control is often applied to diodes,[3,4] However, in this technique, it is difficult to control the lifetime reduction with the diffusion of lifetime killer such as Au or Pt, or the irradiation of high-energy electrons in the fabrication.[5] If the lifetime control affects the base region by the over diffusion or irradiation, then the conductivity modulation disappears and the forward voltage drop severely increases. No tradeoff exists between recovery time and forward voltage drop.

To achieve the tradeoff between recovery time and forward voltage drop, the band gap engineering of SiGe/Si heterojunction is applied and many significant results has been obtained.[6−8] Meanwhile, many researches have considered that SiGe is not suitable for high voltage devices, especially at high temperature, because the lattice mismatch between SiGe and Si poses severe limits on the engineering of Si-based heterostructures.[9] The addition of carbon into the SiGe system yields the SiGeC alloys, whose Ge and C percentages can be adjusted to give a lattice-matched combination with silicon.[10] This ability to lattice match SiGeC with Si removes the stability constraints on the epilayer thickness grown on silicon substrates, which extends the device design space. The SiGeC diodes are proposed by our research group for the first time.[11] The purpose of this study is to examine the reverse recovery characteristics and mechanism of SiGeC p-i-n diodes. By comparing the disappearing course of excess carriers in n^- region, the mechanism of diodes improvement in reverse recovery characteristics is analysed. At the same time, the reverse recovery characteristics of SiGeC diodes versus temperature are also discussed in this paper. In addition, the improvements of p-i-n diodes by introducing lifetime control or by heterojunction band gap engineering are compared in detail.

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2. Device structure and models

The schematic cross section of SiGeC power diodes is shown in Fig.1. The diode has a structure of p^+-SiGeC (anode) /n^--Si /n^+-Si (cathode). The doping level of p-SiGeC layer is $1.0\times10^{19}\text{cm}^{-3}$. The thickness of SiGeC layer is as long as 40 nm. Compared with p^+(SiGe)-n^--n^+ diodes, the structure of SiGeC diodes with carbon atoms has more flexibility in the thickness of p^+(SiGeC) layers, which can be changed from tens of nanometres to hundreds of nanometres. Based on this, the novel diodes overcome some limits to the epitaxial growth of SiGe on Si substrate and reduce process cost for further steps of device process.

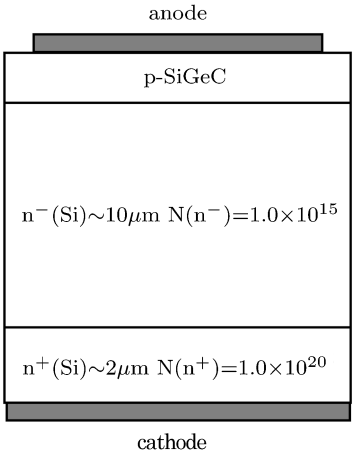


Fig.1. Schematic cross section of SiGeC power diodes.

In order to achieve realistic results, this paper gives several important physical models, which are used in integrated systems engineering (ISE) and applicable for SiGeC power diodes.

2.1. Band gap

The temperature-dependence of the band gap model for SiGeC alloys is expressed as[12−13]

$$E_{\text{g}}(T) = E_{\text{g,Si}} + \Delta E + \frac{\alpha T_0^2}{T_0+\beta} - \frac{\alpha T^2}{T+\beta}, \qquad (1)$$

where T is the lattice temperature, T_0=300 K, α=4.73×10^{-4} eV/K, β=636–401x+30000y K, $E_{\text{g,Si}}$ is the silicon band gap energy at 300 K, and ΔE is the band offsets for SiGeC alloys strained on Si at 300 K.

As a function of the germanium content (x) and carbon content (y), the values of ΔE depend on the strain type of SiGeC alloys. For $y < x/8.2$ the SiGeC layer is compressively strained on the Si substrate. In contrast, for $y > x/8.2$ the alloy is tensely strained. There is a detailed presentation of ΔE in another paper.[14]

2.2. Band gap narrowing

In the novel structure of SiGeC diodes presented in this paper, the doping concentration of p^+(SiGeC) is $1.0\times10^{19}\text{cm}^{-3}$. In that case, the effects of band gap narrowing must be considered. Based on the low carbon content, the band gap narrowing of SiGeC alloys can be computed by the formula[15]

$$\Delta E_{\text{g,A}} = 825x - 2600y + 18\ln\frac{N_{\text{A}}}{10^{17}}, \qquad (2)$$

where N_{A} is the accepter concentration of p^+(SiGeC) layer.

2.3. Mobility

Based on the ISE manual and experimental data[16] of Ahoujja *et al*, the expression of hole mobility is

$$\mu = \mu_{\min}(T/T_0)^{-0.87} + \frac{\mu_{\max}(T/T_0)^{-2.23}}{1+\left(\dfrac{N_{\text{total}}}{N_0(T/T_0)^{2.4}}\right)^{0.7(T/T_0)^{-0.146}}}, \qquad (3)$$

where $N_{\text{total}} = N_{\text{A}} + N_{\text{D}}$ denotes the total concentration of ionized impurities, N_0=2.35×10^{17} cm^{-3}, $\mu_{\min}$=125(1+25x^2−17y−900y^2) cm^2/Vs, $\mu_{\max}$=430−49.7(30x^2 − 17y − 900y^2) cm^2/Vs, T_0=300 K, and T is the lattice temperature.

3. Results and discussion

For high frequency circuits, the reverse recovery characteristics of power diodes are very important. And thus, the fast and soft characteristics are needed for the recovery process of power switching diodes. Power diodes are charge control devices and the change of their working states is not as fast as metal-oxide-semiconductor (MOS) devices. The carrier dissipation of n^- region is the main factor in determining the reverse recovery characteristics of p-i-n diodes. The typical reverse recovery curve of diodes is shown in Fig.2. The reverse recovery time (t_{rr}) of diodes includes two parts. One is storage period (t_a) and the other is fall period (t_b). The softness factor

(S) is defined by t_b/t_a. The higher the value of S is, the better the reverse recovery characteristics are.

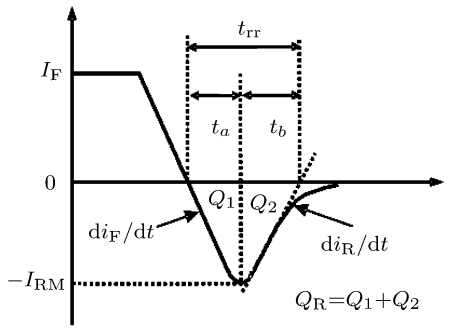


Fig.2. Reverse recovery current of p-i-n diodes.

Based on charge control, the change rate of excess charges in n^- region can be calculated by

$$\frac{dQ}{dt} = i(t) - \frac{Q}{\tau}, \tag{4}$$

where τ is carrier lifetime of n^- region. In the beginning of the reverse recovery process, the forward current (I_F) of diodes is constant, that is, $dQ/dt=0$. In this case, the excess charges are expressed as

$$Q = \tau \cdot I_F. \tag{5}$$

On the other hand, based on the reverse recovery current curves, the reverse recovery charges of diodes are given by

$$Q = \int_0^{t_{rr}} i(t)dt = \frac{1}{2} I_{RM} t_{rr}. \tag{6}$$

From Eqs.(5) and (6), the reverse recovery time t_{rr} can be expressed as

$$t_{rr} = t_a + t_b = 2\tau \frac{I_F}{I_{RM}}. \tag{7}$$

Figure 3 shows the comparison of reverse recovery characteristics between Si and SiGeC diodes with the same device structure and parameters. It can be seen that, compared with Si diodes, the reverse recovery characteristics of SiGeC diodes are more superior, the recovery process is faster and softer, and the reverse peak current is also decreased notably. Take the SiGeC diodes with 20% of germanium and 0.5% of carbon for example, the softness factor increases over six times, reverse recovery time is over 30% short and there is a 20% decrease in peak reverse recovery current, compared with Si diodes.

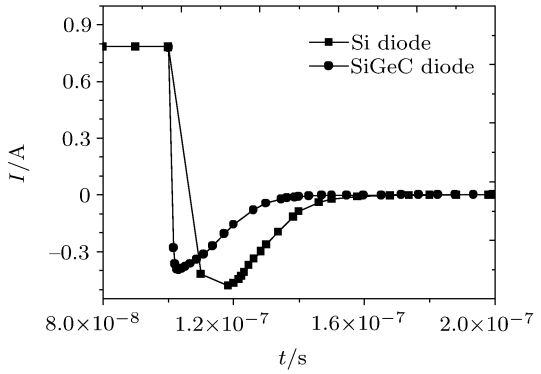


Fig.3. Comparison of reverse recovery characteristics between SiGeC and Si diodes.

Figures 4 and 5 show the electrons and holes contribution of diodes in the course of reverse recovery. The time marked by 't' in Figs.4 and 5 is the same as the time marked on the abscissa of Fig.3. From Figs.4 and 5, it can be seen that the speed of carriers drawing off is much faster in SiGeC diodes than that in Si diodes.

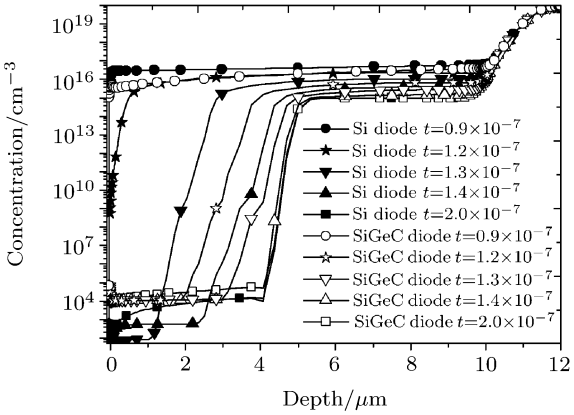


Fig.4. Electrons contribution of inner device in the course of reverse shutdown.

In SiGeC diodes with forward conducting state, due to ΔE_C (conduction band gap offsets) and ΔE_V (valence band gap offsets) on the interface of SiGeC/Si, the carriers stored in SiGeC diodes are less than those in Si diodes and the carriers contribution tilts to one side. The carrier amount near n^--n^+ junction is larger than that near p^+-n^- junction. This phenomenon can be found from Figs.4 and 5. When the reverse bias is applied to SiGeC diodes, the depletion layer is formed at p^+-n^- junction and then begins to extend to n^--n^+ junction. And thus, when the diodes are shutdown, the p^+-n^- junction with low carrier concentration is blocked earlier. In that case,

amounts of carriers are still stored in n^- region and disappear by recombination, it is equivalent to the increase of t_b. And therefore, the SiGeC diodes can achieve the softer recovery characteristics.

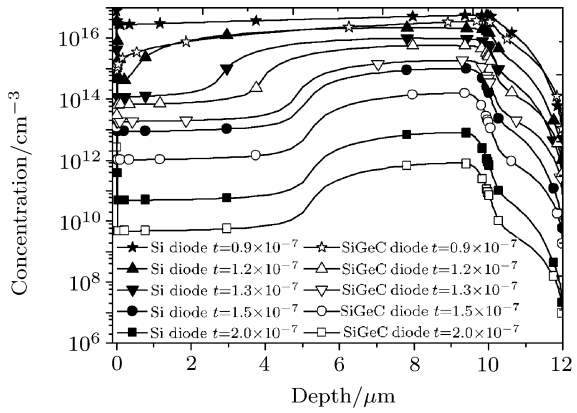


Fig.5. Holes contribution of inner device in the course of reverse shutdown.

The reverse recovery characteristics of diodes can be improved by lifetime control. But the shortage of lifetime control is due to the pact that the tradeoff between reverse recovery time and forward voltage drop can not be achieved. When lifetime control is applied to improve the reverse recovery characteristics of p-i-n diodes, the conductivity modulation disappears and the forward voltage drop severely increases.

Figure 6 shows the comparison of forward $I-V$ characteristics between Si diodes with lifetime control and SiGeC diodes. The lifetime control is applied to Si diodes to decrease its recovery time. The reverse recovery characteristics of two types of diodes are shown in the inset of Fig.6.

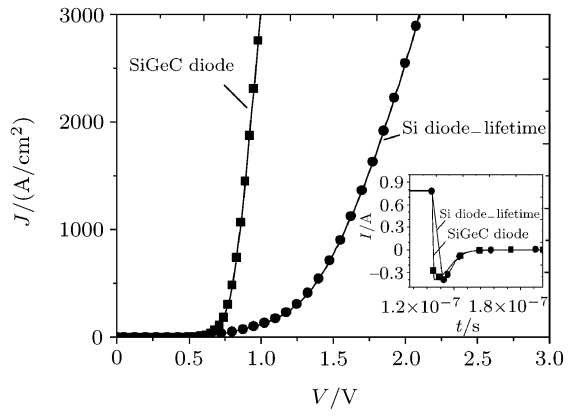


Fig.6. Comparison of forward $I-V$ characteristics between SiGeC diodes and Si diodes with lifetime control.

From Fig.6, it can be seen that the forward conducting characteristics of SiGeC diodes is far superior to Si diodes with lifetime control. The forward voltage drop of SiGeC diodes with 1000 A/cm^2 of current density is about 0.85 V, while the voltage drop of Si diodes with the same current density is 1.59 V. Compared to Si diodes with lifetime control in n^- region, SiGeC diodes keep lower forward voltage drop with high current density transmission. It is highly possible that SiGeC reduces the reverse recovery time of p-i-n diodes without increasing the forward voltage drop.

In addition, from the inset of Fig.6, it can be seen that the recovery time of Si diodes is almost the same as that of SiGeC diodes, but its softness factor is not as high as SiGeC diodes. This indicates that the SiGeC technique is more suitable for improving the reverse recovery characteristics in comparison with lifetime control.

Figure 7 shows the comparison of reverse recovery characteristics between SiGeC diodes and SiGe diodes at different temperatures. Though the reverse recovery time of two types of diodes both increases with increasing temperature, the recovery characteristics of SiGeC diodes are far better than that of Si diodes, especially for high temperature. The recovery time of two kinds of diodes is almost the same at 300 K. Compared to SiGe diodes, the recovery time of SiGeC diodes is decreased by 16.6% at 320K and by 36.4% at 350 K. Furthermore, the reverse recovery current of SiGe diodes can not reach to zero at 350K and this phenomenon is more serious at 400 K. It can be concluded that the advantages of SiGeC to improve the reverse recovery characteristics of p-i-n diodes are more obvious with increasing of temperature.

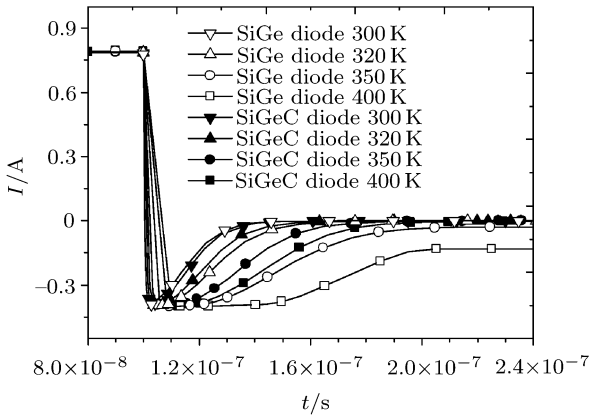


Fig.7. Comparison of reverse recovery current between SiGeC diodes and SiGe diodes at different temperatures.

The major drawback in the use of SiGe/Si for high performance devices is the relatively large lattice

mismatch between Si and Ge. Such a mismatch leads to strain-relieving and the formation of misfit dislocations if the layer thickness exceeds a critical value or operating temperature of devices rises. The dislocation may introduce interface states in the band gap due to their fields and dangling bonds. As a result, they may introduce generation-recombination centre that will increase reverse leakage current.

The improvements of SiGeC diodes are attributed to the less lattice misfit f, between the interface of SiGeC/Si. The misfit for SiGeC on Si substrate can be calculated by

$$\begin{aligned} f =&(\alpha_{\mathrm{SiGeC}} - \alpha_{\mathrm{Si}})/\alpha_{\mathrm{Si}} \\ =&x(\alpha_{\mathrm{Ge}} - \alpha_{\mathrm{Si}})/\alpha_{\mathrm{Si}} + y(\alpha_{\mathrm{C}} - \alpha_{\mathrm{Si}})/\alpha_{\mathrm{Si}}, \end{aligned} \quad (8)$$

where α_{SiGeC} can be estimated for a ternary system of SiGeC using Vegard's law and assuming full relaxation,

$$\alpha_{\mathrm{SiGeC}} = \alpha_{\mathrm{Si}} + x(\alpha_{\mathrm{Ge}} - \alpha_{\mathrm{Si}}) + y(\alpha_{\mathrm{C}} - \alpha_{\mathrm{Si}}), \quad (9)$$

where x and y are the percentage of germanium and carbon contents, respectively. From Eqs.(8) and (9), it can be seen that the lattice constant of SiGeC alloys can be adjusted to agree with Si by altering the Ge:C ratio. The strain within SiGeC system can be reduced or compensated by adding small-sized carbon atoms into SiGe alloys and the misfit is decreased. Therefore, the performance of SiGeC diodes can be improved remarkably, especially at high temperature.

4. Conclusion

The fast and soft reverse recovery process must be required for power switching diodes to satisfy the demands of high frequency trend of power electronic technique development. The heterojunction band gap engineering is introduced to improve the reverse recovery characteristics of p-i-n diodes. The softness factor increases over six times, reverse recovery time is over 30% short and there is a 20% decrease in peak reverse recovery current for SiGeC diodes with 20% of germanium and 0.5% of carbon in comparison with Si diodes. By analysis of the reverse recovery characteristics of SiGeC diodes at different temperatures, it can be concluded that the advantages of SiGeC to improve the reverse recovery characteristics of p-i-n diodes are more and more obvious with increase of temperature. Compared to Si diodes with lifetime control in n^- region, the tradeoff between reverse recovery time and forward voltage drop can be easily achieved in SiGeC diodes, that is, it is highly possible that SiGeC reduces the reverse recovery time of p-i-n diodes without increasing the forward voltage drop.

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