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A novel type of ultra fast and ultra soft recovery SiGe/Si heterojunction power diode with an ideal ohmic contact*

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A novel type of p^+(SiGe)–n^-–n^+ heterojunction switching power diode with high-speed capability is presented to overcome the drawbacks of existing power diodes. The improvement is achieved by using a p^+–n^+ mosaic layer as a substitute for the n^+ region in the conventional p^+(SiGe)–n^-–n^+ diode to realize an 'ideal ohmic' contact for electrons and holes simultaneously. Compared with conventional p^+(SiGe)–n^-–n^+ diodes, the ideal ohmic contact p^+(SiGe)–n^-–n^+ diodes have about one third of the reverse recovery time and a half of peak reverse recovery current. Furthermore, the softness factor increases nearly two times and the leakage current decreases 1–2 orders of magnitude. These improvements are achieved without resorting special process step to lower the carrier lifetime and thus the devices could be easily integrated into power ICs. The Ge percentage content of p^+(SiGe) layer is an important parameter for the optimal device design.

Keywords: SiGe/Si heterojunction, power diode, ideal ohmic contact, ultra fast and ultra soft recovery

PACC: 7340L

1. Introduction

A key device in all high voltage AC–DC power supplies is the fast reverse recovery rectifier diode. The rectifier would generally need to have low forward conducting voltage drop, minimum reverse leakage current, and fast and soft reverse recovery process for high frequency switching operation. The performance of state-of-the-art silicon PiN diodes is now approaching the theoretical limits, and it is apparent that further advances in silicon technology are very difficult due to its material properties.[1] With the widespread use of silicon germanium (SiGe) material in advanced heterojunction bipolar transistors (HBTs) and bipolar complementary metal-oxide semiconductor (BiCMOS) technology in modern IC technology, the shallow SiGe/Si heterojunction becomes an important constituent of the devices. The p^+(SiGe)–n^-–n^+ power diodes have been gradually attached great importance because of notably improving the characteristics of Si PiN diodes and their compatibility with Si IC process.[2–4] The simulation results on conventional p^+(SiGe)–n^-–n^+ heterojunction power diodes carried out by us [3] are in good agreement with experimental results presented by Brown.[2]

In this paper, a novel type of p^+(SiGe)–n^-–n^+ heterojunction power diode with high-speed capability is presented. The improvement is achieved by using 'universal contact', which has a p^+–n^+ mosaic layer on the cathode interface and acts as an 'ideal ohmic' contact for electrons and holes simultaneously. The universal contact remarkably decreases the reverse recovery time and leakage current, resulting in a higher operating temperature limit. The p^+(SiGe)–n^- junction is ultra-shallow junction whose depth is tens of nanometres. In addition, based on analysing the structure and mechanism of the devices, we optimize the Ge percentage content in the p^+(SiGe) layer.

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2. Device structure

The structure of conventional p^+(SiGe)–n^-–n^+ diodes is shown in Fig.1(a), which is analogous to the structure of Si PiN diodes except that the $p^+(Si_{1-x}Ge_x)$–n^-–n^+ diodes have a $p^+(Si_{1-x}Ge_x)$ layer with thickness of about 20–50nm. The n^- region thickness can be changed according to the requirement of undergoing the reverse blocking voltage. The n^-n^+ interface 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. At the influence of the electric field any minority carriers (holes in this case) which approached the interface turn back from the interface, as illustrated in Fig.1(b). For power diodes, the reflection of minority carriers can be detrimental to achievement of fast turn-off time because they would be trapped in the n^- region.

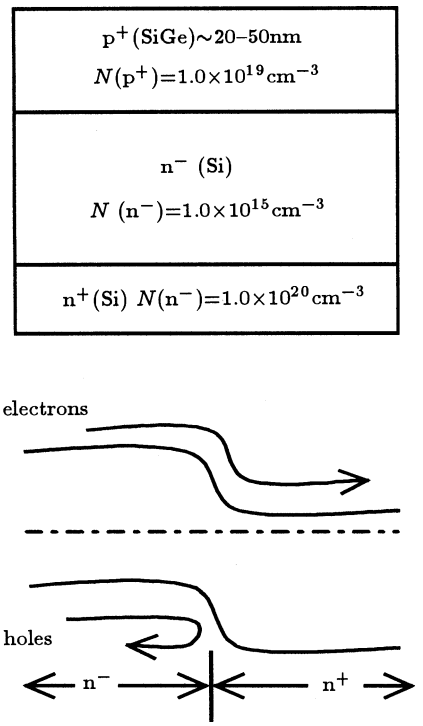


Fig.1. (a) The structure for conventional p^+(SiGe)–n^-n^+ diode, (b) the band diagram for conventional n^-n^+ contact.

For achieving faster and softer reverse recovery characteristics, we introduce a novel type of $p^+(Si_{1-x}Ge_x)$–n^-–n^+ heterojunction power diode with a p^+–n^+ mosaic structure substituted for the n^+ region to obtain an ideal ohmic contact that can allow the transport of holes and electrons simultaneously across the interface. The structure of the novel device and its composite band diagram are shown in Figs.2(a) and (b). In this contact, the p^+ regions provide an ohmic contact for holes whereas the n^+ regions provide the conventional ohmic path for electrons, resulting in faster reverse recovery characteristics.

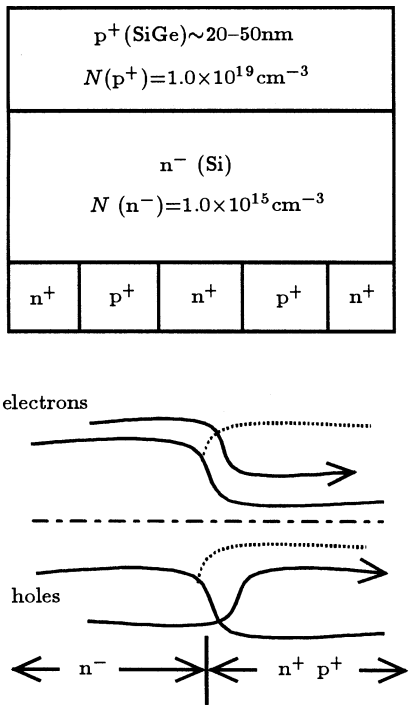


Fig.2. (a) The structure for p^+(SiGe)–n^-–n^+ diode with ideal ohmic contact, (b) the band diagram for ideal ohmic contact.

3. $Si_{1-x}Ge_x$ material parameters

The simulated results of the device depend critically on adopted physical models; thus, in order to achieve realistic results, several important material parameters used in MEDICI,[5] such as bandgap and mobility of carriers, are adjusted to obtain the closest agreement with published data of SiGe material. The formulae on the bandgap, bandgap narrowing and carriers mobility *et al* in strained $Si_{1-x}Ge_x$ alloy as a function of impurity density, temperature and Ge content x are in reasonable agreement with the theoretical and experimental results given by the literature when Ge content is relatively small.

To describe accurately bandgap in the $Si_{1-x}Ge_x$ alloy, the following empirical formula presented by Bean [6]

$$E_{g,SiGe}(x,T) = E_{g,Si}(T) - 0.96x + 0.43x^2 - 0.17x^3 (eV)$$

is applied. This empirical formula on the bandgap of strained $Si_{1-x}Ge_x$ alloy is in good agreement with ex-

perimental data and the other literature [7,8] when the Ge content does not exceed 0.6.

$E_{g,Si}(T)$ is expressed by [9]

$$E_{g,Si}(T) = 1.17 + 1.059 \times 10^{-5}T - 6.05 \times 10^{-7}T^2(\text{eV})$$

$$(T = 0 - 190\text{K})$$

and

$$E_{g,Si}(T) = 1.1785 - 9.025 \times 10^{-5}T - 3.05 \times 10^{-7}T^2(\text{eV})$$

$$(T = 150 - 300\text{K}),$$

where x is the Ge percentage content in the SiGe alloy and T is absolute temperature.

The bandgap narrowing in heavily doped $Si_{1-x}Ge_x$ strained layers depend weakly on Ge content as it does not exceed 30% according to research results,[10,11] and these results are accorded with the bandgap narrowing modelling of p-type Si and n-type Si proposed by Klaassen,[12] so we apply Klaassen's modelling

$$\Delta E_{g,A} = K_1 \left| \ln\left|\frac{N}{K_2}\right| + \sqrt{\left|\ln\left|\frac{N}{K_2}\right|\right|^2 + C} \right|$$

to describe the bandgap narrowings, $\Delta E_{g,A}$, of p-type strained SiGe layers, where K_1=6.29meV; K_2=1.3×10^{17}cm^{-3}; C=0.5, N is doping concentration.

The expression on electron mobility of strained $Si_{1-x}Ge_x$ layers at room temperature is given by [13]

$$\mu_n = \left[\frac{\mu_{n,max} - \mu_{n,min}}{1 + (N_A/N_0')^\beta}\right] \times (1 + a_1 x + a_2 x^2 + a_3 x^3) + \mu_{n,min},$$

where $\mu_{n,max}$=1350cm^2/(V·s), $\mu_{n,min}$=175cm^2/(V·s), N_A is doping concentration, $a_1 = -3.02$, $a_2 = -7.08$, $a_3 = 53.08$, N_0'=1.1×10^{17} (1+14.65x)cm^{-3}, β=5/8. The expression is in good agreement with the calculation results by Key [14] and the empirical equation in the literature.[15]

The hole mobility of strained $Si_{1-x}Ge_x$ at room temperature is given by [16]

$$\mu_p = \frac{\mu_{p,0}}{1 + (N_A/N_0)^\beta} + \mu_{p,min}.$$

where, $\mu_{p,0} = 400 + 29x + 400x^2$(cm^2/(V · s)), $\mu_{p,min} = 44 - 20x + 850x^2$ (cm^2/(V · s)), $N_0 = 2.35 \times 10^{17}$cm^{-3}, $\beta = 0.9$.

The dielectric constants of $Si_{1-x}Ge_x$ material is expressed by [17]

$$\varepsilon = \varepsilon_4 + [(\varepsilon_{300} - \varepsilon_4)/296](T - 4).$$

where

$$\varepsilon_4 = 11.4(1 - x) + 15.4x; \ \varepsilon_{300} = 11.7(1 - x) + 15.8x.$$

4. Simulation results and analysis

We simulate and compare the reverse recovery current characteristics and forward, backward I–V characteristics of both the conventional p$^+$(SiGe)–n$^-$–n$^+$ diodes with different thicknesses of the n$^-$ region ranged between 8μm and 12μm and the novel type of p$^+$(SiGe)=-n$^-$-=n$^+$ diodes with that between 10μm and 16μm in MEDICI.

The P$^+$(SiGe) layer thickness is 20nm for all the diodes and, apart from a mosaic of p$^+$ and n$^+$ regions substituting the n$^+$ region, the novel p$^+$(SiGe)–n$^-$–n$^+$ diodes are assumed to have the same dimensional features as the conventional ones in order to compare conveniently. In Figs.3(a), 4 and 5, the symbols followed by the word 'mosaic' represent ideal ohmic contact p$^+$(SiGe)–n$^-$–n$^+$ diodes, others represent conventional p$^+$(SiGe)–n$^-$–n$^+$ diodes and the numbers are the thickness of n$^-$ region for corresponding diode.

Figure 3(a) shows the comparison of the reverse recovery current characteristics of the devices with conventional contact and with ideal ohmic contact having different n$^-$ region thicknesses. It can be seen from the simulation results that the reverse recovery process of the novel device is not only much faster but also much softer than that of the conventional device. Also it can be seen that the peak reverse current notably decreases which is very important for the fast switch diodes. Take the two types of p$^+$(SiGe)–n$^-$–n$^+$ diodes with the same n$^-$ region thickness of 10 μm, for example: reverse recovery time is about two-thirds shorter and there is a 50% decrease in peak reverse recovery current; moreover, the softness factor S is nearly double for the diodes with the ideal ohmic contact compared with the conventional contact.

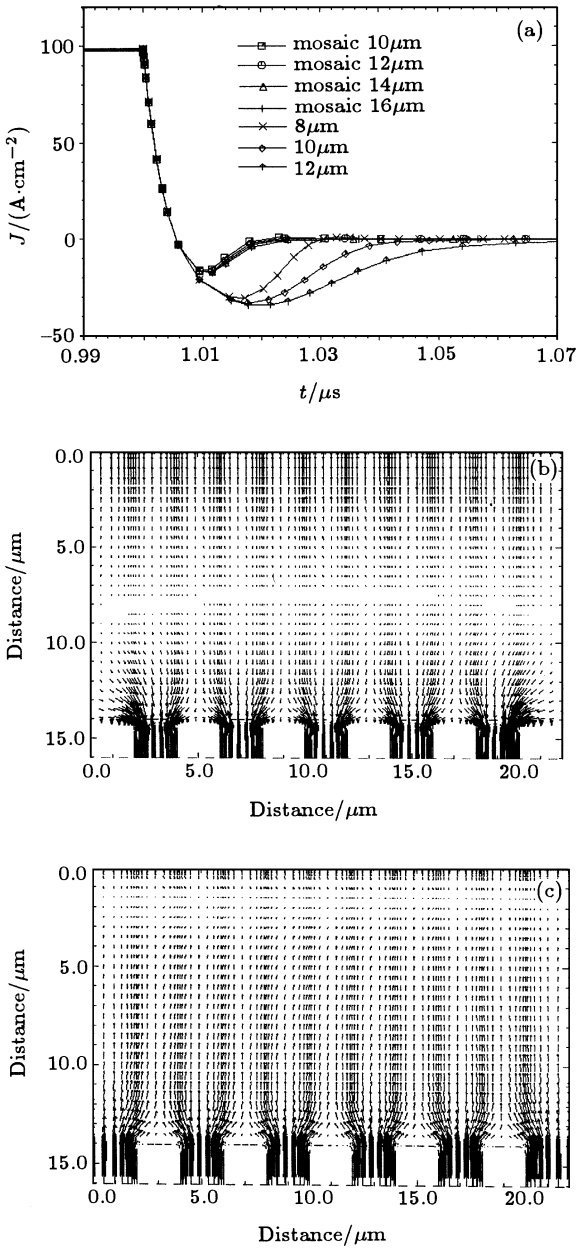


Fig.3. (a) The comparison of reverse recovery current characteristics between conventional and ideal ohmic contact p^+(SiGe)–n^-–n^+ diodes with different n^- region thicknesses, (b) The hole current vectors in an ideal ohmic contact p^+(SiGe)–n^-–n^+ diode for the transition from forward bias to reverse bias, (c) The electron current vectors in an ideal ohmic contact p^+(SiGe)–n^-–n^+ diode for the transition from forward bias to reverse bias.

These carriers injected from the anode and cathode regions during forward conduction must be removed from the n^- region to sustain the reverse blocking voltage. The carriers either flow by reverse current out of the anode and cathode or recombine in the middle of the n^- region. When a heavily doped p^+–n^+ mosaic layer is inserted as the contact between metal and semiconductor instead of the former n^+ layer, the minority carriers (holes) reaching the contact boundary are not reflected but are absorbed smoothly into the p^+ regions (see Fig.3(b)), while the majority carriers (electrons) can easily be supplied through the n^+ regions (Fig.3(c)), resulting in the great decrease of reverse recovery time. The enhancement of sweeping carriers speeds the form of space charge layer across the anode and the cathode junctions to sustain the majority of reverse voltage, while there are still many free carriers in the middle of the n^- region to disappear by recombination; hence the soft recovery characteristic is also improved.

An important result can be obtained from Fig.3(a) that reverse recovery time is almost unchanged when the n^- region thickness has a small increase for the novel p^+(SiGe)–n^-–n^+ diodes, whereas the recovery time is increased greatly for the conventional ones.

Figure 4 shows the comparison of the forward I–V characteristics for two types of p^+(SiGe)–n^-–n^+ diodes. The forward voltage drop of the novel p^+(SiGe)–n^-–n^+ diode is almost same as that of the conventional one as the current density is lower than $100A/cm^2$; however, the forward I–V characteristic is degenerate as the current density is higher than $100A/cm^2$. The reason is that when the diode is forward biased, the n^-p^+ junction in the vicinity of the

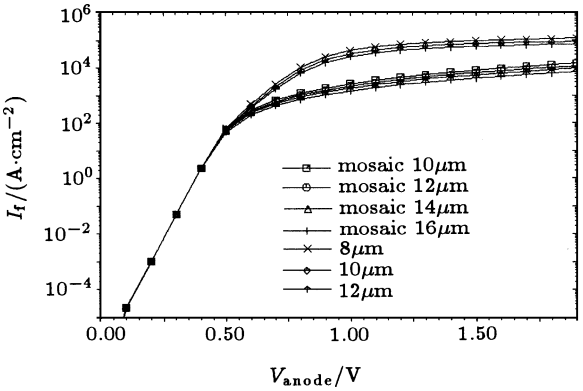


Fig.4. The comparison of forward I–V characteristics between conventional and ideal ohmic contact p^+(SiGe)–n^-–n^+ diodes with different n^- region thickness.

cathode is in the state of reverse bias so as to weaken the effects of conductivity modulation. This phenomenon is more obvious at very high current density. But, in fact, we can ignore the negative effect to forward voltage drop due to introducing the p^+-n^+ mosaic layer. The typical value of current densities in the on-state is $100A/cm^2$;[18] the corresponding value of forward voltage drop is about 0.5V for both ideal ohmic contact p^+(SiGe)–n^-–n^+ diode and the

conventional one. Even if the current densities reach 1000A/cm^2, the forward voltage for the ideal ohmic contact p$^+$(SiGe)–n$^-$–n$^+$ diode is only 0.1V larger than that for the conventional one. Actually, power devices integrated into power ICs usually work at current densities no larger than 1000A/cm^2. In addition, we can adjust the thickness of the p$^+$ region in the p$^+$–n$^+$ mosaic layer to improve the forward conducting characteristic, which will be discussed in another paper.

A shortcoming of the novel type of diode is that, as shown in Fig.5, the reverse block voltage greatly decreases compared with the conventional diode with the same n$^-$ region thickness. Although the reverse block voltages of the two types of p$^+$(SiGe)–n$^-$–n$^+$ diodes increase with the increase of n$^-$ region thickness, the increment of reverse block voltage of the former is greater than that of the latter when both of the p$^+$(SiGe)–n$^-$–n$^+$ diodes have the same increment of n$^-$ region thickness. When the power diode is reverse biased, the space charge (depletion) layers across the p$^+$n$^-$ junction and n$^-$n$^+$ junction sustain the reverse blocking voltage. After the p$^+$–n$^+$ mosaic layer substitutes the former n$^+$ layer, the effective area of the n$^-$n$^+$ junction is reduced hence yielding an increase in inner electric field of the junction. Impact ionization occurs more easily resulting in the decrease of reverse block voltage.

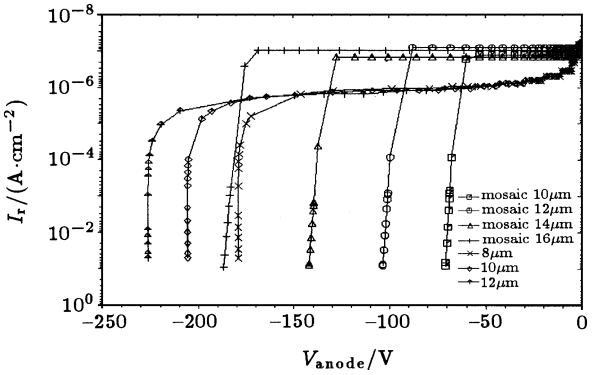


Fig.5. The comparison of reverse $I-V$ characteristics between conventional and ideal ohmic contact p$^+$(SiGe)–n$^-$–n$^+$ diode with different n$^-$ region thickness.

However, a considerable merit of p$^+$(SiGe)–n$^-$–n$^+$ diodes with ideal ohmic contacts, as can be seen from Fig.5, is that the leakage current of novel devices is 1–2 orders of magnitude lower than that of the conventional one. This feature allows their operation at higher ambient temperature.

5. The optimal design of Ge percentage content

The percentage content of Ge element is an important parameter for the device design. Comparison of different content of Ge in the p$^+$(SiGe) layer (from 0% to 30%) is shown in Figs.6(a)–(c). For characteristics simulation, the thicknesses of p$^+$(SiGe) layer, n$^-$ region and p$^+$-n$^+$ mosaic layer are respectively chosen as 20nm, 14μm and 2μm. The mosaic-pitch, i.e. repeat distance, is 2μm and the ratio of n$^+$ to p$^+$ areas is 1:1.

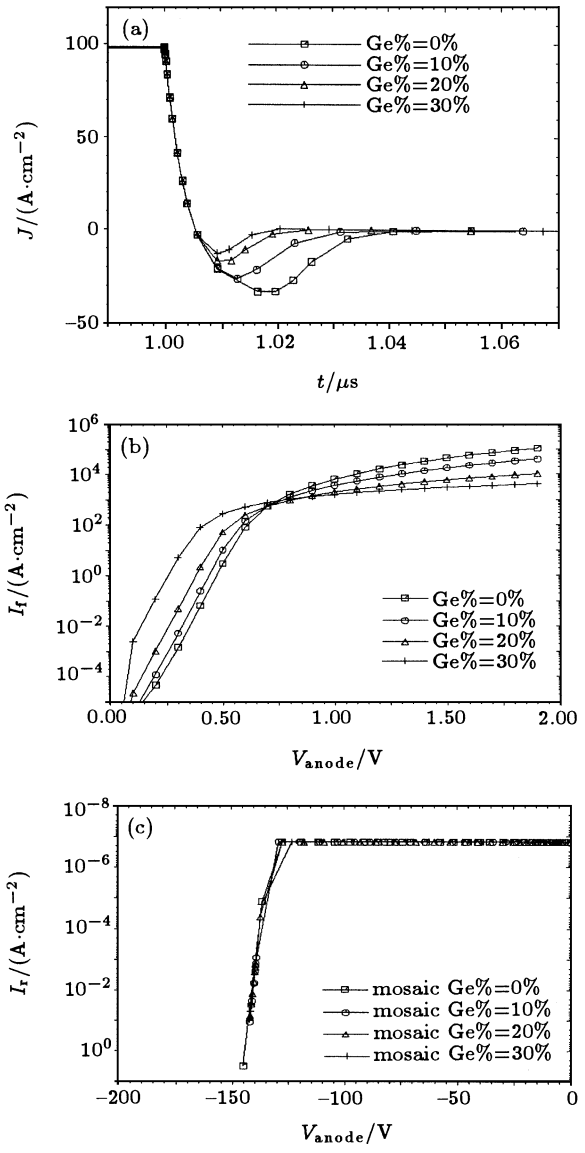


Fig.6. (a) Comparison of the reverse recovery current characteristics of ideal ohmic contact p$^+$(Si$_{1-x}$Ge$_x$)–n$^-$–n$^+$ diodes with different Ge content, (b) comparison of the forward $I-V$ characteristics of ideal ohmic contact p$^+$(Si$_{1-x}$Ge$_x$)–n$^-$–n$^+$ diodes with different Ge content, (c) comparison of the backward $I-V$ characteristics of ideal ohmic contact p$^+$(Si$_{1-x}$Ge$_x$)–n$^-$–n$^+$ diodes with different content of Ge.

Figure 6(a) shows that the peak reverse current is lessened notably, the recovery time decreases significantly and the soft recovery characteristics are much improved with the increase of the Ge content. From Fig.6(b) it can be seen that the forward voltage drop reduces with the increase of the Ge content as the current density is lower than $10^3 A/cm^2$ which is higher than that of the general situation, while the current density is higher than $10^3 A/cm^2$, and the forward voltage drop increases with the increase of the Ge content. Figure 6(c) shows that the reverse leakage current and reverse block voltage is almost unchanged by the Ge content.

Because of lattice mismatch (about 4%), Si and Ge are crystallographically incompatible. When the thickness of a $Si_{1-x}Ge_x$ epilayer exceeds a composition-dependent value (critical thickness), misfit dislocation networks form at the SiGe/Si interface with accompanying threading dislocations grown into the SiGe epilayer to release the mismatch strain in heterostructures. The high density of threading dislocations formed in SiGe epilayers results in material degradation and deterioration of device performance.[19] The critical thickness is quite small for high Ge percentage content; thus, to obtain a high merit SiGe strained layer on a silicon substrate, the germanium content is usually not too high. Considering this factor and the tradeoff between reverse recovery current and forward I–V characteristics, we think that 20% germanium in the SiGe layer is reasonable.

6. Conclusions

A novel type of p^+(SiGe)–n^-–n^+ heterojunction switching power diodes with p^+–n^+ mosaic layer substituting the conventional n^+ layer to realize ideal ohmic contact is proposed. The new type of device shows ultra fast and ultra soft reverse recovery characteristics and far lower leakage current so that the safe operation area is notably wide. An important merit of the novel p^+(SiGe)–n^-–n^+ diode is that the reverse recovery current characteristics are only slightly sensitive to the n^- region thickness while the reverse block voltage is very sensitive to it: the reverse recovery time and softness factor S are almost unchanged but the reverse block voltage is remarkably increased when the n^- region thickness is slightly increased. These characteristics are very useful for design of the device. Under the condition of meeting the demand of forward voltage drop, the n^- region thickness can be increased properly in order to increase the reverse block voltage, while the reverse recovery time and softness factor S are almost unchanged. In addition, we optimize the Ge percentage content of the p^+(SiGe) layer. All of these results are very important for the design and manufacture of the p^+ ($Si_{1-x}Ge_x$)–n^-–n^+ heterojunction power diodes.

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