High-performance germanium n^+/p junction by nickel-induced dopant activation of implanted phosphorus at low temperature*

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High-performance Ge n^+/p junctions were fabricated at a low formation temperature from 325 °C to 400 °C with a metal(nickel)-induced dopant activation technique. The obtained NiGe electroded Ge n^+/p junction has a rectification ratio of 5.6×10^4 and a forward current of 387 A/cm^2 at −1 V bias. The Ni-based metal-induced dopant activation technique is expected to meet the requirement of the shallow junction of Ge MOSFET.

Keywords: germanium, metal-induced dopant activation, NiGe, n^+/P junction

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1. Introduction

Germanium (Ge) has been considered as the best candidate to replace the traditional Si to fabricate next-generation metal–oxide–semiconductor field-effect transistors (MOSFET) because of its high carrier mobilities. However, the low activation level and fast diffusion of the implanted phosphorus (P) in Ge hinder the formation of high-quality shallow Ge n^+/p junctions.[1] As a result, Ge n-MOSFET is confronted by more process challenges as compared to its p-MOSFET counterpart.[2]

To fully activate the dopant atoms as well as to control the dopant redistribution depth, a metal-induced dopant activation (MIDA) technique has aroused much research interest recently. Park et al. studied dopant activation of α-Ge by films of various metals including Pd, Cu, Au, Co, and Ni (Nickel).[3] According to his results, Ni was not considered as a good choice to activate the implanted P dopant atoms because Ni itself acts as acceptor-like traps in Ge. Later, Nishimura et al. fabricated Ge n^+/p junctions by Ni/NiGe induced dopant activation.[4] However, the rectification ratio of the junctions is only about 10^3, which is one order of magnitude lower than the junctions formed by the Pt[5] and Co[6] induced dopant activation.

Ni and Ni germanide (NiGe) have been widely used as the source/drain contact in Ge MOSFET. When the Ni film was annealed on the implanted Ge to facilitate MIDA, NiGe simultaneous formed even at temperatures as low as 300 °C. NiGe film has a resistivity of 22 μΩ·cm which is the lowest among all metal germanides as far as we know.[7] On the other hand, as the top Ge is consumed during the NiGe formation, a snow-plow effect[8] may accumulate dopant atoms at the germanide/Ge interface which is favored for low-contact-resistivity shallow junction fabrication.

In this work, we demonstrate high performance Ge n^+/p junctions formed by low temperature annealing from 325 °C to 400 °C with Ni-induced dopant activation. A rectification ratio of 5.6×10^4 and high forward current of 387 A/cm^2 were obtained.

2. Materials and methods

P-type Ge(001) wafer with a resistivity of 0.06 Ω·cm and undoped Ge(100) wafer with a resistivity of 50 Ω·cm were cleaned by acetone, ethanol, HCl solution, and finally dipped by HF solution. After being covered with 15-nm-thick SiO_2 by plasma-enhanced chemical vapor deposition, these wafers were implanted by P^+ ions with the acceleration voltage of 30 keV and the dose of 1×10^{15} cm^{-2}. After the top SiO_2 buffer layer was stripped, 25-nm-thick Ni was deposited in an e-beam evaporation system. The Ni film was then patterned by optical lithography and HCl solution ($HCl:H_2O = 1:1$) etching. Using the patterned photoresist as a shield, ICP etching continuously etched the exposed Ge to form circular junction plateaus with a diameter of 160 μm. The Ge etching depth was set 800 nm to make sure all the exposed Ge implantation layers were totally removed. The photoresist was then stripped and the samples execute thermal annealing at temperatures from 325 °C to

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400 °C in nitrogen atmosphere for 30 min to perform MIDA. NiGe layer formed as well. 300 nm of Al was finally deposited on the back side of the samples for ohmic contact.

As a comparison, n^+/p junctions by conventional rapid thermal annealing (RTA) were also prepared. The cleaning, implantation, and Ni deposition were the same as above. However, before SiO_2 stripping and Ni deposition, the wafers were pre-annealed at the 550–650 °C temperature range for 15 s to replace the MIDA annealing. A 400 °C/30 s annealing was used to form NiGe electrode.

3. Results and discussion

In a conventional Ge n^+/p junction process, the implanted P^+ atoms require an RTA annealing over 500 °C to be fully activated. Figure 1 shows the sheet resistance measurements on the implanted Ge after various RTA activation annealing. To avoid influence from the conducting Ge substrate, undoped Ge was used for ion implantation. From Fig. 1, annealing temperatures from 550 °C to 650 °C are suitable to fully activate the implanted P dopants as judged by the low sheet resistance of the annealing sample. Such high annealing temperature inevitably causes the P dopants to diffuse prominently in Ge.

As observed by many studies, the Ge surface was severely damaged and even transformed into α-Ge after high-dose ion implantation. High temperature annealing is required to recrystallize the top amorphous layer as well as to activate the dopants. The α-Ge has been reported to be fully crystallized at above 450 °C.[7] However, in MIDA, the diffused metal atoms in the implanted Ge weaken the bonds in Ge and lower the temperature for homogeneous nuclei formation. As the nuclei grew into crystals, the dopant atoms are also rearranged and activated subsequently. To find a suitable MIDA temperature for NiGe electroded n^+/p junction preparation, the (25 nm) Ni was annealed on undoped Ge to check the resistance and the material phase. Figures 2 and 3 show the sheet resistance measurements and the x-ray diffraction results. From the diffraction data, Ni has been transformed to NiGe at temperatures as low as 300 °C. The resistance is not low enough until after 325 °C/30 min annealing. The formed NiGe film was rather smooth after 30 min annealing form 325 °C to 400 °C as viewed by scanning electron microscopy (not shown). After high temperature annealing above 550 °C, the films start to agglomerate. Hence, the suitable MIDA temperature was set from 325 °C to 400 °C.

Current–voltage (I–V) characteristics were measured on the MIDA Ge n^+/p junctions. Figure 4(a) shows the four typical I–V curves for samples annealed at 325 °C, 350 °C, 375 °C, and 400 °C. Apart from the sample annealed at 325 °C, the other samples all showed rectification ratios larger than 10^4. The best sample (activated at 400 °C) showed a rectification ratio of 5.6×10^4 and a forward current density

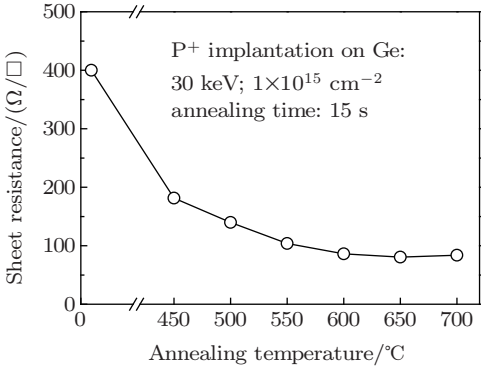


Fig. 1. Sheet resistance of the implanted Ge after RTA annealing from 450 °C to 700 °C.

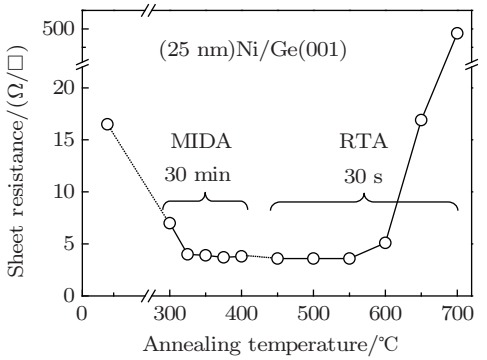


Fig. 2. Sheet resistance of the (25 nm)Ni/Ge(001) after annealing.

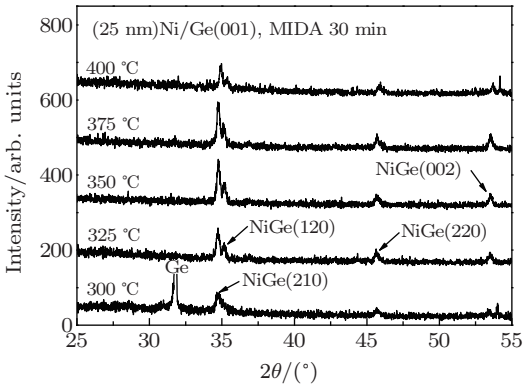


Fig. 3. X-ray diffraction patterns of the (25 nm)Ni/Ge(001) after annealing for 30 min at various temperatures.

of 387 A/cm^2. As a comparison shown in Fig. 4(b), the n^+/p junction formed by convention high temperature activation has the best rectification ratio of 2.8×10^4. Therefore, the Ni-induced dopant activation was also successful in fabricating a high-quality n^+/p junction but with much lower process temperature. The extracted ideality factors for the above four samples are listed in Table 1. These values ranged from 1.05 to 1.14, which further confirmed the diffusion current to be the main carrier transport mechanism in the n^+/p junctions.

We also tried P^+ implantation through thick SiO_2 windows to fabricate MIDA Ge n^+/p junctions. However, the measured IV curves show a rectification ratio only about 10^2. As is known, there are a large number of surface states when

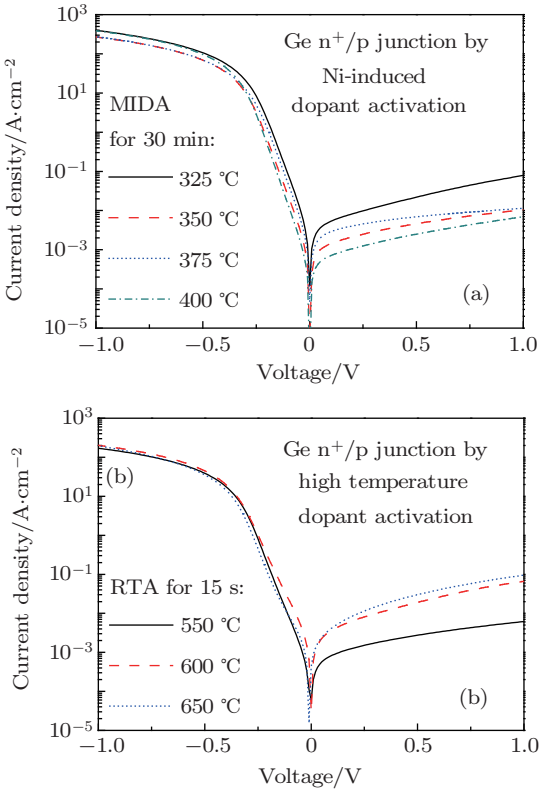


Fig. 4. (color online) (a) Typical *I–V* curves for the MIDA Ge n^+/p junctions annealed at 325 °C, 350 °C, 375 °C, and 400 °C; (b) typical *I–V* curves for the Ge n^+/p junctions after high temperature activation annealing at 550 °C, 600 °C, and 650 °C.

Table 1. Rectification ratios and extracted ideality factors of Ge n^+/p junctions fabricated by various dopant activation methods.

Dopant activation	Rectification ratio	Ideality factor
MIDA 325 °C/30 min	5.0×10^3	1.13
MIDA 350 °C/30 min	2.6×10^4	1.12
MIDA 375 °C/30 min	2.4×10^4	1.14
MIDA 400 °C/30 min	5.6×10^4	1.05
RTA 550 °C/15 s	2.8×10^4	1.12
RTA 600 °C/15 s	3.1×10^3	1.29
RTA 650 °C/15 s	2.0×10^3	1.15

Ge directly contacts with SiO_2, which contributed to the leakage path across the edge of the n^+/p junctions. Hence, a good surface passivation method could be important to reduce the leakage current at negative bias and increase the rectification ratio of the Ge n^+/p junctions.

The corresponding P, Ni, Ge elemental distributions were measured by secondary ion mass spectroscopy (SIMS) as shown in Fig. 5. The as-implanted Ge sample has a peak dopant concentration of 4×10^{20} cm^{-3}. After dopant activation, the concentration was reduced to 2×10^{20} cm^{-3} for both 350 °C/30 min and 550 °C/15 s annealed samples. The 550 °C RTA annealed sample shows a box-like dopant redistribution profile which is typical for phosphorus diffusion in Ge. The RTA sample also produced a longer concentration tail than the MIDA sample. In the conventional 550 °C RTA annealing, the dopants diffuse very fast along the paths which are comprised of many lattice damages formed by ion implantation. In MIDA, such diffusion paths are annihilated together with Ge recrystallization. The low process temperature helps to suppress the diffusivities of the dopants as well. Hence, the final dopant distribution profile did not change very much as compared to the original implanted dopant profile. From the viewpoint of the shallow junction technology, MIDA is much preferred over the RTA annealing.

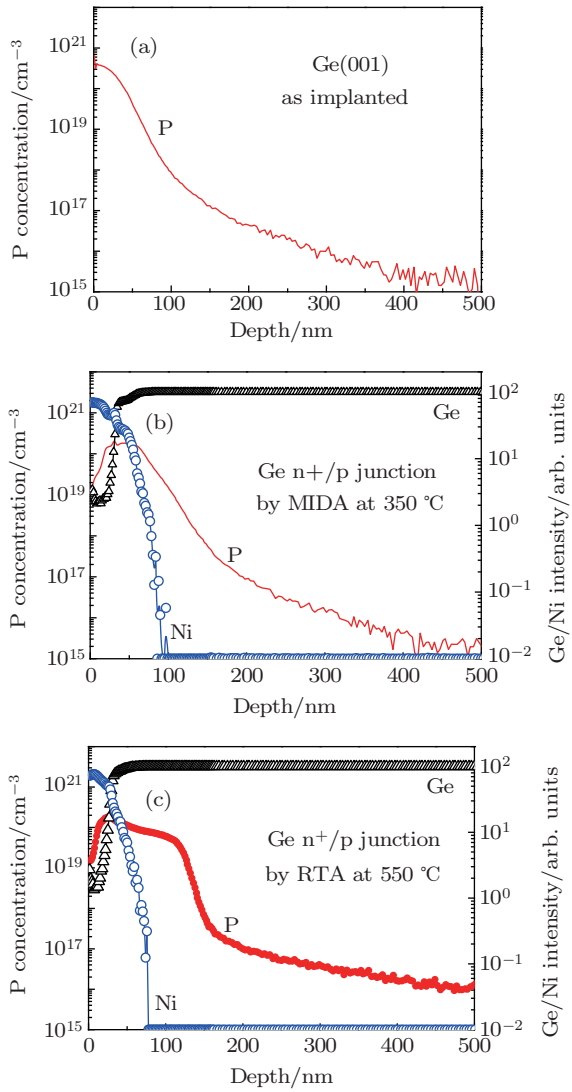


Fig. 5. (color online) P, Ni, and Ge distribution profiles measured by SIMS for (a) Ge(100) substrate after P^+ implantation, (b) Ge n^+/p junction after MIDA annealing at 350 °C for 30 min, and (c) Ge n^+/p junction after RTA activation annealing at 550 °C for 15 s.

The Ni film was transformed into NiGe phase after annealing. Figure 5 shows that the Ni concentration dropped sharply at the NiGe/Ge(100) interface and totally disappeared (below the detection limit of SIMS) after etching Ge for 60 nm because the solid solubility of Ni in Ge is very low (2×10^{11} cm^{-3} at 450 °C[9]). The P concentration is still higher than 1×10^{19} cm^{-3} at the depth that the Ni trace disappeared. So we concluded that the Ni diffusion in Ge(100) is generally quite limited in the sense of the concentration. The Ni diffusion should not have any notable compensation effect

on the activated implanted P dopants even if all the Ni atoms in Ge act as acceptor-like traps. The low concentration of Ni impurities in Ge provides another reason to contribute the high rectification ratio of the Ge n^+/p junctions shown in Fig. 4(a).

The snow-plow effect was not observed because the Ni film in our experiment is not thick enough. The P dopants distribute across the NiGe/Ge(100) interface and within the shallow surface of the Ge substrate, but not yet reaching the outside surface of the NiGe layer. By tuning the process parameters such as reducing the P^+ implantation energy or using a thicker Ni layer, the P distribution throughout the NiGe layer and the n^+/p junction could be modulated. An optimized implantation/germanidation process combined with the MIDA annealing can be beneficial to forming a shallow junction which is required by the scaling MOSFETs.

4. Conclusions

In summary, using Ni as the metal layer for MIDA of the implanted P dopant in Ge, a high rectification ratio of 5.6×10^4 and a forward current of 387 A/cm^2 at -1 V bias is obtained for Ge n^+/p junction. The high rectification ratio is ascribed to the suppression of the surface leakage and limited diffusion of the Ni in Ge. SIMS shows that the P redistribution in the MIDA junctions is less significant that the junctions activated at high temperatures. The MIDA Ge n^+/p junction may find its application in novel Ge n-MOSFET.

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