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Electrical Properties of Multiple High-Dose Si Implantation in p-GaN

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This work performs Si ion implantation the electrical conductive type of the p-GaN film from p-type to n-type. Multiple implantation method is also used to form a uniform Si implanted region in the p-type GaN epitaxial layer. Implant energies for the multiple implantation are 40, 100, and 200 KeV. The implant dose is 5×10^{15} cm^{-2} for each implant energy. After implantation, the samples are annealed in a N_2 ambient for different annealing temperatures and annealing times. The activation efficiency reaches as high as 20% when annealing the sample at 1000°C. The carrier activation energy is about 720 meV. The low activation energy indicates that the hopping process mechanism is the dominant mechanism for the activation of the Si implantation in p-GaN. Moreover, the rectifying *I-V* characteristic of the p-n GaN diode is also examined.

KEYWORDS: GaN, implantation, activation energy

III–V nitrides have been extensively applied in areas interest for applications such as blue light sources and UV detectors.[1–6] In addition, this material system is attractive for use in high temperature and high power electronic devices. To integrate electronic circuits, a selective doping technology must be developed to define the device structure. The ion implantation technology with a well controlled doping profile is employed in Si integrated circuits, GaAs metal semiconductor field-effect transistors (MESFET) in digital integrated circuits, and GaAs MESFET in monolithic microwave integrated circuits. Early studies of ion implantation for III-nitride materials focused mainly on investigating the p-type dopants for the realization of light emitting diodes. Recent studies involving ion-implanted GaN materials have concentrated on studying implanted impurities for n-type donors, p-type acceptors and atoms for electrical isolation. In addition, the ion implantation for n-type and p-type dopants of GaN has already been investigated, such as the Si and O atoms used for n-type dopants,[7,8] Mg and Ca atoms used for p-type dopants,[7] and H, N, and F atoms used for electrical isolation.[7,9] While most related studies discussed the activation efficiency of implanted ions, their results indicated that the activation of implanted impurities in GaN is much more difficult than in conventional compound semiconductors, such as GaAs and InP. As the implant dose is below 1×10^{15} cm^{-2}, the reported activation efficiency of Si implants ranged from 0.1% to 94%.[7,10] However, for high-dose Si implants, Zopler *et al*. demonstrated that the high-dose Si implant (1×10^{16} cm^{-2}) can be annealed at 1100°C to obtain an activation efficiency of ∼50%.[10] Much of the variability in reported results for low-dose implants is probably due to the different quality of the used GaN epitaxial layer. In this letter, we elucidate the electrical properties of Si implantation in p-GaN. The Hall measurement of the implanted n^+ layer and the *I-V* characteristic of the n^+-p diodes are also measured.

The p-type GaN layer used in this experiment was grown on a *c*-plane sapphire substrate using a commercial metal-organic chemical vapor deposition (MOCVD) system. During the growth, a 25 nm thick GaN buffer layer was initially grown at 525°C and, then, a 1.88 μm thick Mg-doped p-type GaN was deposited at 1050°C. After growth, the samples were annealeding in nitrogen ambient to activate the p-type dopants. The carrier concentration and Hall mobility of the p-GaN epitaxial layer were 1.5×10^{17} cm^{-3} and 11 cm^2/V·s, respectively. After to activate the p type dopants, the Si implantation was performed in the commercial implanter system. Notably, the SiF_4 gas was used as the Si source. To avoid localizing the implanted Si atoms at a fixed depth, the multiple implantation with three different implant energies was used in this study. The implant energies were 40 keV, 100 keV, and 200 keV. The dose was 5×10^{15} cm^{-2} for each implant. The projective ranges (R_p) simulated from TRIM-95 are 552, 1391, and 2898 Å for the Si implant energy of 40 keV, 100 keV and 200 keV, respectively. The relative projective straggles (ΔR_p) correspond to 319, 707, and 1277 Å. After the implantation the samples were annealed in a N_2 ambient atmosphere by using a conventional furnace. Next, different annealing temperatures and annealing times were used to realize the effects of thermal annealing treatment for activation the Si implantation samples. After annealing, the samples were first characterized by the Hall measurement to obtain the room-temperature sheet carrier concentrations and Hall mobilityes. The samples were then used to fabricate the homojunction GaN n^+-p diodes. The procedure is described as follows. The sample was first etched at a depth of 1.2 μm to expose the p-type contact region by using a ICP-RIE system. Ti/Al and Ni/Au were then used as the metals for n-type and p-type ohmic contacts, respectively. After metallization, the *I-V* characteristics were measured by the HP-4145 semiconductor parameter analyzer.

Figure 1 illustrates an Arrihenius plot of the room-temperature sheet carrier concentration versus the annealing temperature for the Si implantation in p-GaN. The annealing time was fixed at 30 minutes. According to this figure, the conduction types of the samples were inverted from p-type to n-type and the sheet carrier concentrations were increased when increasing the annealing temperature. As the sample was annealed at 750°C, the activation efficiency of the implanted Si atoms was only about 4.5%. When the annealing temperature was increased to 1000°C, the amount of activated Si atoms was as high as 20% of the implant dose. Figure 1 also indicates that the activation energy of the implanted Si atoms can be fitted to be 720 meV. This energy is significantly smaller than that reported by Zopler *et al*. The

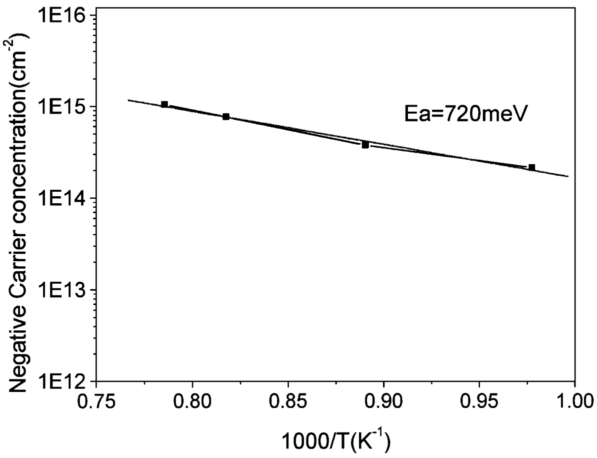

Fig. 1. Relationship between the sheet carrier concentration and annealing temperature. The annealing time was 30 min. The estimated carrier activation is 750 meV.

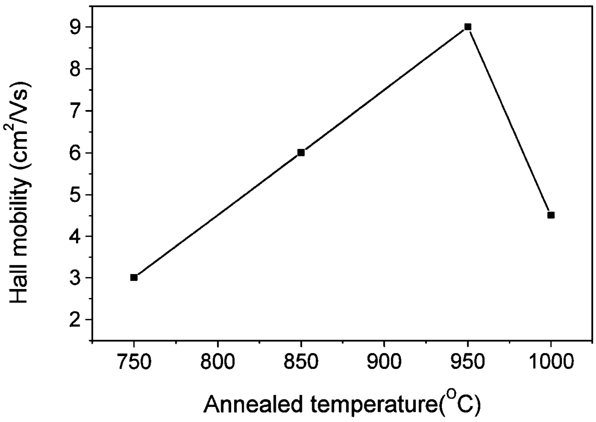

Fig. 2. Relationship of the Hall mobility versus the annealing temperature. The annealing was kept at 30 min.

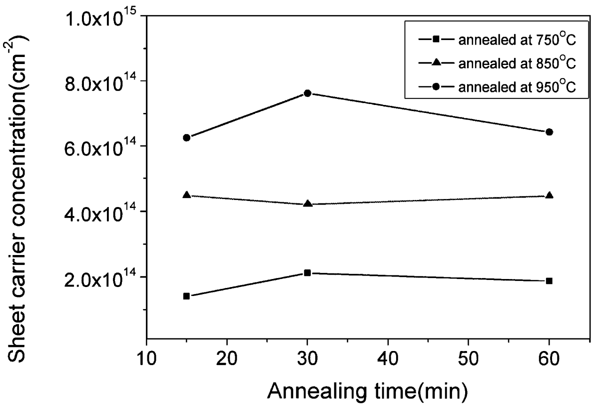

Fig. 3. The sheet carrier concentration, which almost did not change with the annealing time.

carrier activation energy reported by Zopler was 6.2 eV, and the activation mechanism was resulted from the substitutional diffusion process. In addition, their results also indicated that the carrier activation energy of 6.7 eV[11] was comparable to the activation energy of the intrinsic diffusion coefficient for GaAs.[12] The difference of the activation energies between 6.7 eV and 0.72 eV are probably due to the different implantation conditions. The implanted dose of Zopler's studies was lower than that used in this study and was only 1×10^{15} cm^{-2}, which was lower than the critical implant dose to amorphize the GaN layer. As the crystal structure was amorphized by the high-dose Si implant, much more defects and dislocations might appear in the implanted GaN region. Therefore, when the crystal structure was amorphized, the Si atoms easily occupy a lattice site to be activated as donors during the thermal annealing treatment.

In addition, a single high-energy implant (100 keV) with a localized Si doping profile would result in a non-uniform implanted region, inducing the increase of measurement errors for the Hall measurement. The multiple implantation used in this study supplied a uniform Si implanted in the p-GaN layer and, in doing so, the accuracy of the Hall-effect measurement was increased more than before.

In addition to the activation energy, the mechanism for Si implantation in this study may also be significantly different from the study of Zopler *et al*. The high implant dose in this study will result in a large amount of point defects in the implanted region. Therefore, the activation mechanism is not only due to the substitutional process. Previous studies found the hopping process to be the dominant mechanism for GaAs and InP to activate the implanted atoms. The activation energy for the hopping process ranges from 0.4 to 1.9 eV.[13–16] This process either places an interstitial atom on a vacancy site or breaks up a complex defect of the dopant with a neighboring vacancy. As the multiple energy high-dose implantation created a large amount of defects, the activation mechanism for Si implantation in p-GaN is more closely resembles the hopping process than the substitutional process as the implant dose was as high as 5×10^{15} cm^{-2}.

Figure 2 depicts the relationship between the Hall mobility and the annealing temperature. According to this figure, the mobility ranges from 3 to 9 cm^2/V·s. Although markedly differing from the standard n-type epitaxial layer, the mobility is comparable to that of the original p-type GaN (11 cm^2/V·s) since most of the atoms were not activated among the implanted region. This same figure indicates that the room-temperature for Hall mobility was increased when increasing the annealing temperature as the annealing temperature was below 950°C. This occurrence was attributed to that the implanted crystal structure was recrystallized at high annealing temperature. When the temperature was exceeded 950°C, most of the Si atoms were activated as donors. These activated Si atoms might be attributed to the increase of the impurity scattering and the reduction of the Hall mobility. Regarding the effect of annealing time on the activation efficiency, the annealing time was varied from 15 min to 1 hour. Figure 3 reveals that the carrier concentration did not increase when increasing the annealing temperature. This phenomenon indicates that the annealing time of 15 min is sufficient for the electrical activation. Moreover, the activation efficiency heavily depends on the annealing temperature.

Figure 4 presents the *I-V* curve of the Si implanted GaN homojunction diode. The turn on voltage of the p-n junction diode was 12 V. The forward current was about 30 μA at a bias voltage of 30 V. According to this figure, the reverse breakdown voltage of the p-n junction diode was not observed even though the applied reverse bias was up to -30 V. Al-

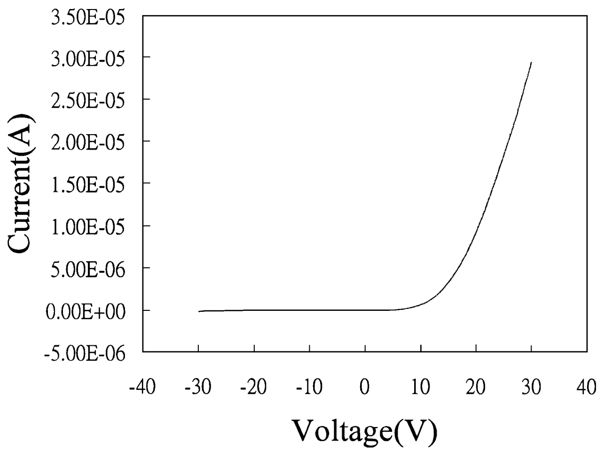

Fig. 4. *I-V* characteristics of the Si implanted p-n junction diode.

though the *I-V* is not good enough, the rectification characteristic is obviously observed. The high turn-on voltage may be due to the damages induced by the high-energy implantation of 200 keV.[17] To improve the *I-V* characteristics, a low implant energy and a optimized implant dose are required to reduce the turn-on voltage.

Using conventional thermal treatment, this study performed Si implantation in p-GaN to activate and convert the electrical conduction of GaN from p-type to n-type by the conventional thermal treatment. The carrier activation energy of 720 meV was also estimated. In addition, the hopping process was considered and appeared to be the dominant mechanism of the activation process for the Si implantation in p-GaN. The activation efficient of Si implantation in p-GaN heavily depended on the annealing temperature, and was insensitive to the annealing time. For the first time, this study has successfully fabricated the GaN p-n junction diode by using the multiple high-dose Si implantation in p-GaN. This technique is highly promising for fabricating the GaN-base optical and electrical devices.

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