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Electrical Properties of the Si Implantation in Mg Doped p-GaN

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This work performs Si ion implantation to activate and convert the electrical conduction of p-GaN films from p-type to n-type. Multiple implantation method is used to form a uniform Si implanted region in the p-type GaN epitaxial layer. Implantation energies for the multiple implantation are 40, 100, and 200 keV. The implantation dose is $5 \times 10^{15} \text{ cm}^{-2}$ for each implantation energy. After implantation, the samples were annealed in an 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 implant in p-GaN. In addition, the rectifying I - V characteristic of the p-n GaN diode is also examined.

1. Introduction

III-V nitrides are of special interest for their applications as blue light sources and UV detectors [1 to 6]. In addition, this material system is attractive for use in high temperature and high power electronic devices. For 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 of 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, ion implantation of n-type and p-type dopants in GaN has already been investigated, such as Si and O atoms used for n-type dopants [7 to 9], Mg and Ca atoms used for p-type dopants [7], and H, N, and F atoms used for electrical isolation [7, 10]. In this paper, 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.

2. Experiment

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 annealed in a nitrogen ambient to activate the p-type dopants. The carrier concentration and Hall mobility of the p-GaN epitaxial layer were $1.5 \times 10^{17} \text{ cm}^{-3}$ and $11 \text{ cm}^2/\text{Vs}$, respectively. After activating the p-type dopants, Si implantation was performed in the commercial implanter system. Notably, SiF_4 gas was used as the Si source. To avoid localization of the implanted Si atoms at a fixed depth, multiple implantation with three different implantation energies was used in this study. The implantation energies were 40, 100, and 200 keV. The dose was $5 \times 10^{15} \text{ cm}^{-2}$ 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, 100 and 200 keV, respectively. The relative projective straggles (ΔR_p) correspond to 319, 707, and 1277 Å, respectively. After the implantation the samples were annealed in an N_2 ambient atmosphere. Next, different annealing temperatures and annealing times were used to realize the effects of thermal annealing treatment for the activation of the Si implanted samples. After annealing, the samples were first characterized by Hall measurements to obtain the room-temperature sheet carrier concentrations and Hall mobilities. The samples were then used to fabricate 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.

3. Result and Discussion

Fig. 1a illustrates an Arrhenius 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 min. According to this figure, the conduction type of the samples was inverted from p-type to n-type and the sheet carrier concentration increased with increasing 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 implantation dose. Figure 1a 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. [9]. The carrier activation energy reported by Zopler was 6.7 eV, and the activation mechanism 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 and 0.72 eV is probably due to the different implantation conditions. The implanted dose in Zopler's studies was lower than that used in this study and was only $1 \times 10^{15} \text{ cm}^{-2}$, which was lower than the critical implantation dose to amorphize the GaN layer. As the crystal structure was amorphized by the high-dose Si implant, much more defects and disloca-

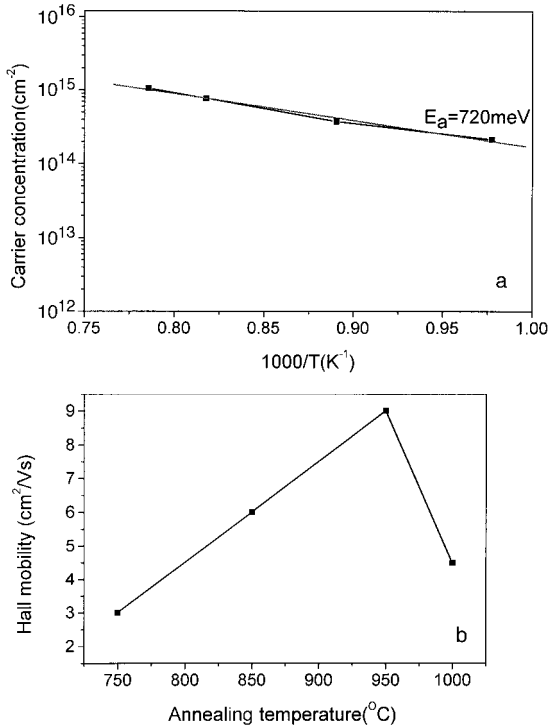


Fig. 1. a) Relationship between the sheet carrier concentration and annealing temperature. The annealing time was 30 min. The estimated carrier activation is 750 meV. b) Relationship of the Hall mobility was kept versus the annealing temperature. The annealing at 30 min

tions 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 in the Hall measurement. The multiple implantation used in this study supplied a uni-

form Si implantation 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 implantation 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 to 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 resembles more closely the hopping process than the substitutional process as the implantation dose was as high as $5 \times 10^{15} \text{ cm}^{-2}$.

Figure 1b depicts the relationship between the Hall mobility and the annealing temperature. According to this figure, the mobility ranges from 3 to 9 cm²/Vs. Although markedly differing from the standard n-type epitaxial layer, the mobility is comparable to that of the original p-type GaN (11 cm²/Vs) since most of the atoms were not activated among the implanted region. This same figure indicates that the room-temperature Hall mobility was increased when increasing the annealing temperature up to 950 °C. This occurrence was attributed to the fact that the implanted crystal structure was recrystallized at high annealing temperature. When the temperature exceeded 950 °C, most of the Si atoms were activated as donors. These activated Si atoms might

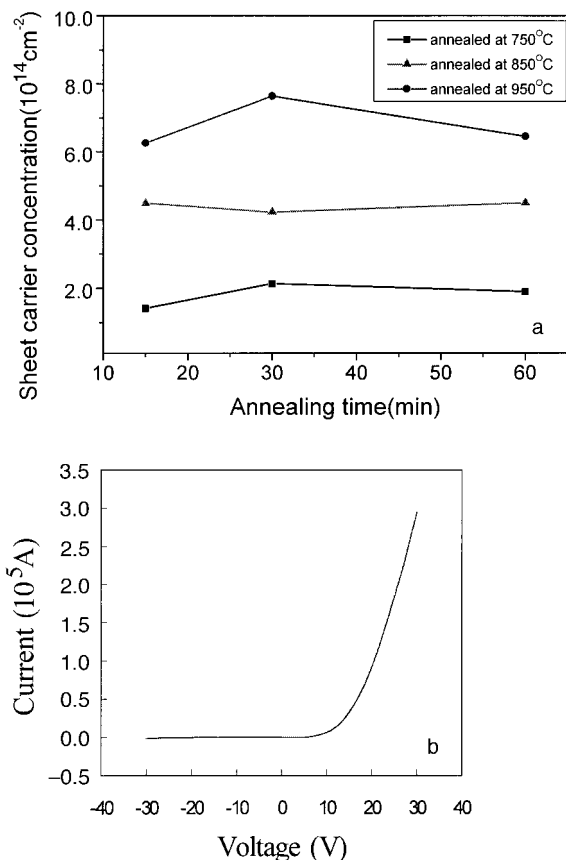


Fig. 2. a) Sheet carrier concentration, which almost did not change with the annealing time. b) I - V characteristics of the Si implanted p-n junction diode

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 h. Figure 2a reveals that the carrier concentration did not increase with increasing annealing temperature.

Figure 2b 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 $30 \mu\text{A}$ at a bias voltage of 30 V. Although the I - V curve is not good enough, a 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 implantation energy and optimized implantation dose are required to reduce the turn-on voltage.

4. Conclusions

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. A carrier activation energy of 720 meV was 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 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 GaN p-n junction diodes by using the multiple high-dose Si implantation in p-GaN. This technique is highly promising for fabricating GaN-base optical and electrical devices.

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