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Implantation-induced electrical isolation of GaAsN epilayers grown by metalorganic chemical vapor deposition

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The electrical isolation of p -type GaAs_{1-x}N_x epilayers ($x=0.6\%$, 1.4% , and 2.3%) produced by H, Li, C, or O ion implantation and its thermal stability in nominally undoped GaAs_{0.986}N_{0.014} epilayers were investigated. Results show that the sheet resistance of p -type GaAsN layers can be increased by about five or six orders of magnitude by ion implantation and the threshold fluence (F_{th}) to convert a conductive layer to a highly resistive one depends on the original free carrier concentration and the number of implantation-generated atomic displacements, and does not depend on the nitrogen content. The thermal stability of electrical isolation in GaAsN depends on the ratio of the final fluence to the threshold fluence. The electrical isolation can be preserved up to 550°C when the accumulated fluence is above $3.3 F_{th}$. © 2003 American Institute of Physics.

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Incorporation of a few percent of nitrogen (N) into GaAs causes an extraordinary reduction of the band gap and a modification of the conduction-band structure, which have attracted considerable theoretical and experimental interest.¹⁻⁷ Recently, the unusual band-gap reduction has been interpreted using the band anticrossing model.³ A wide range of semiconductor devices, such as $1.3\ \mu\text{m}$ semiconductor lasers and heterojunction bipolar transistors,^{2,4} have been fabricated using III-V dilute nitride alloys. Unfortunately, the crystal quality and optical properties are very poor for as-grown III-V dilute nitride alloys and postgrowth annealing is necessary to improve device properties.⁵ Many defect studies have indicated that postgrowth annealing reduces the concentration of defects remarkably, leading to improved alloy properties.^{6,7} However, these studies were focused on grown-in defects and no work has been done on implantation-induced defects. Implantation-induced electrical isolation, one of the applications of these defects and a major processing step to fabricate HBTs and multiple section lasers,⁸ of p -type GaAsN epilayers has been investigated in this work.

In general, there are two mechanisms responsible for the implantation-induced electrical isolation, which are carrier trapping at either damage-related deep-level centers (defect isolation) or at chemical deep-level states (chemical isolation).⁸ In our study, single energy MeV ions were used to allow us to separate the effects of defect isolation from chemical isolation.⁹

Single energy MeV ion implantation-induced electrical isolation has worked very well in GaAs and AlGaAs epilayers with their relatively large band gaps.^{10,11} However, it is less effective in InGaAs epilayers with small band gaps.⁸ We are not aware of any report demonstrating implantation-induced isolation in GaAsN epilayers, which are always p -type due to background doping during metalorganic chemical vapor deposition (MOCVD) and have smaller band

gaps than GaAs. In this work, the formation and the stability of electrical isolation in GaAsN epilayers were investigated using different ions to understand the effects of N content, original free carrier concentration, ion mass, and ion fluence.

The GaAsN epilayers were grown on semi-insulating (SI) GaAs (100) substrates at 600°C in a modified Thomas Swan MOCVD reactor. Epilayers of 500 nm thick p -type GaAs_{1-x}N_x ($x=0.6\%$, 1.4% , and 2.3%) were grown at 76 Torr on a 200 nm undoped GaAs buffer layer. The different p -type carrier concentrations were obtained by background doping or zinc doping. The free carrier concentration of nominally undoped GaAs_{1-x}N_x ($x=0.6\%$, 1.4% , and 2.3%) are 1.2×10^{17} , 5.0×10^{17} , $1.4\times 10^{18}\ \text{cm}^{-3}$, respectively. All the as-grown GaAsN samples were annealed at 750°C for 30 s in N₂ atmosphere using rapid thermal annealing (RTA) to improve their crystal and optical quality.⁵ The x-ray and photoluminescence measurements have indicated the high quality of the epilayers used in this study.¹²

The annealed wafers were cleaved into rectangular resistors of $6\ \text{mm}\times 4\ \text{mm}$ for implantation. The ohmic contacts were prepared by manually applying indium (In) strips and sintering at 250°C for 2 min. The ohmic behavior of the sintered In contacts has been verified by their linear current-voltage characteristics. The sheet resistances of SI-GaAs wafer and undoped GaAsN epilayers are $\sim 6.3\times 10^9\ \Omega/\text{sq}$ and $\sim 10^3\ \Omega/\text{sq}$, respectively. These resistors were implanted to fluences varying from 2×10^{10} to $3\times 10^{14}\ \text{cm}^{-2}$ with 600 keV $^1\text{H}^+$, 700 keV $^7\text{Li}^+$, 2 MeV $^{12}\text{C}^+$, or 2 MeV $^{16}\text{O}^+$ ion at room temperature (RT) in a 1.7 MV tandem accelerator (NEC, 5SDH-4). The ion energies were chosen to create the essentially uniform ion-generated atomic displacement profiles throughout the conductive GaAsN layers and to place the damage peak deep in the SI-GaAs substrates. This also minimizes any chemical effect of implanted ions on GaAsN conductivity. To minimize channeling effects, the samples were tilted by 7° off the surface normal direction. The sheet resistance (R_s) was measured *in situ* after each fluence step by using a Keithley 617 electrometer. Postimplantation iso-

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FIG. 1. (a) Sheet resistance vs accumulated fluence in p -type $\text{GaAs}_{1-x}\text{N}_x$ epilayers with different N contents "x" and free hole concentrations "p" during 2 MeV $^{12}\text{C}^+$ implantation. (b) p vs threshold fluence obtained from data in (a). The straight line with a slope of $1.1 \pm 0.03 \text{ cm}^{-1}$ representing the best linear fit. Data obtained from Zn-doped GaAs are also shown.

chronal annealing cycles were carried out in the RTA furnace for 60 s at temperatures ranging from 100 to 700 °C in a N_2 ambient. The annealing steps were accumulated in samples and R_s was measured at RT in the dark.

Figure 1(a) shows the fluence dependence of R_s in both nominally undoped (solid symbols) and Zn-doped GaAsN (open symbols) resistors during 2 MeV $^{12}\text{C}^+$ ion implantation at RT. The sheet resistance of all the samples is increased by about five to six orders of magnitude by ion implantation. At first, R_s increases only slightly with the accumulation of dose, and then it increases rapidly to a maximum value after a characteristic fluence, F_{th} , due to carrier trapping and mobility degradation.⁸ This maximum value results from the parallel association of the resistances in isolated layers and the underneath GaAs substrate. When the accumulated fluence exceeds F_{th} , R_s remains unchanged and forms a plateau for the GaAsN epilayer with 0.6% N. However, the plateau becomes narrower and is not observed with the increase of N content or hole concentration. This is because when the accumulated fluence is high enough, defect-assisted hopping conduction¹³ leads to reduction in the sheet resistance. It is also worth stressing that the maximum R_s of samples with high N content or high hole concentration is lower than R_s of undoped GaAsN (0.6% N) due to the compromise between carrier trapping effects and hopping conduction effects from the implantation-induced damage.

Figure 1(b) shows the original free carrier concentration of GaAsN versus F_{th} obtained from Fig. 1(a). The data of Zn-doped GaAs are also shown in Fig. 1(b). It can be seen that F_{th} for p -type GaAs and GaAsN with similar carrier

FIG. 2. (a) Fluence dependence of sheet resistance in undoped $\text{GaAs}_{0.986}\text{N}_{0.014}$ epilayers exposed to $^{16}\text{O}^+$, $^7\text{Li}^+$, and $^1\text{H}^+$ ions. (b) Threshold fluence vs the number of displacements produced by different ions. The best linear fit with a slope of $-1.07 \pm 0.01 \text{ cm}^2$ and the data for 2 MeV $^{12}\text{C}^+$ are also shown.

concentration are very close. Also, all of the data fit on a line with a slope of $1.1 \pm 0.03 \text{ cm}^{-1}$ indicating that F_{th} depends nearly linearly on the original free carrier concentration and does not depend on N content.

Figure 2(a) shows the evolution of R_s of nominally undoped GaAsN (1.4% N) epilayers implanted with 0.6 MeV $^1\text{H}^+$, 0.7 MeV $^7\text{Li}^+$, or 2 MeV $^{16}\text{O}^+$ ions at RT. It is obvious that F_{th} shifts to lower fluences with increasing ion mass. This phenomenon is related to the fact that at a given ion fluence, heavier particles create higher concentrations of atomic displacements in the 500 nm GaAsN epilayers. It can be explained very well by plotting the number of displacements (calculated using the TRIM code)¹⁴ as a function of F_{th} , as shown in Fig. 2(b). The best-fit line with a slope of $-1.07 \pm 0.01 \text{ cm}^2$ indicates that F_{th} is inversely proportional to the defect concentration in GaAsN epilayers. We suspect that changing the density of atomic displacements by varying the ion energy should still result in F_{th} falling on this straight line, similar to our recent results on p -type GaAs.¹⁵

A crucial requirement for isolated devices is that they must retain their high resistance at the working temperature, and, generally, high thermal stability is desirable. Figure 3 shows the postimplantation annealing temperature dependence of R_s of undoped $\text{GaAs}_{0.986}\text{N}_{0.014}$ epilayers implanted with 2 MeV $^{12}\text{C}^+$. Three identical GaAsN resistors implanted to different fluences were used, labeled as F1 = $1.1 F_{\text{th}}$, F2 = $3.3 F_{\text{th}}$, and F3 = $12.5 F_{\text{th}}$ in Fig. 1(a).

During the postimplantation annealing, sample F1 experienced a gradual decrease of R_s with the increase of temperature and the thermal stability is restricted to temperatures around 400 °C. Above 400 °C, a rapid decrease of R_s is

FIG. 3. Annealing temperature dependence of sheet resistance of undoped $\text{GaAs}_{0.986}\text{N}_{0.014}$ epilayers implanted to different fluences “F” with 2 MeV $^{12}\text{C}^+$.

observed and leads to the restoration of the original R_s value at around 650 °C. This is because in sample F1, the number of implantation-induced carrier trapping centers is just greater than the number of free carriers in the GaAsN epilayer, and the elimination of defects during thermal annealing immediately recovers the carrier mobility which leads to the monotonic decrease of R_s . We speculate that in the lower-temperature range (less than 400 °C), only simple defects, like vacancies or interstitials are annealed out, resulting in a partial recovery of carrier mobility and a slow decrease of R_s . Annealing at higher temperatures (>400 °C) could dissolve some defect clusters which are the main carrier trapping centers, leading to a rapid decrease of R_s . A systematic study on annealing kinetics of defects created in implanted GaAsN is warranted to clarify this question. A remarkable improvement in the thermal stability of electrical isolation was observed when the accumulated fluence exceeds $3.3 F_{th}$. It can be seen from the curves of samples F2 and F3 in Fig. 3 that the electrical isolation can persist up to 550 °C, and that there is an initial increase of R_s related to the removal of hopping conduction when the damage is repaired at the early annealing stage.

The study of annealing temperature dependence of R_s in undoped GaAsN epilayers implanted with different ions shows that at a fixed fluence $F = 1.1 F_{th}$, all of the samples exhibit similar behavior indicating that ion mass has a marginal effect on the thermal stability of electrical isolation (not

shown) and the key factor affecting the thermal stability is the ratio of the final fluence to F_{th} .

In summary, we have demonstrated implantation-induced electrical isolation of *p*-type GaAsN epilayers grown by MOCVD. The results reveal that the threshold fluence depends nearly linearly on the concentration of original free carriers and depends inversely on the concentration of atomic displacements produced by the ion beam, and does not depend on the N contents used in this study. The thermal stability of isolation depends on the ratio of the final fluence to the threshold fluence. A fluence of $F = 3.3 F_{th}$ is suggested as the minimum fluence necessary to achieve high thermal stability. This study may have significant technological implications for choosing the necessary implantation conditions for implantation-induced electrical isolation of GaAsN epilayers.

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