AIP Applied Physics Letters

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Citation: Applied Physics Letters **78**, 943 (2001); doi: 10.1063/1.1348306
View online: http://dx.doi.org/10.1063/1.1348306
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/78/7?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

Electrical isolation of GaN by MeV ion irradiation

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(Received 26 October 2000; accepted for publication 19 December 2000)

The evolution of sheet resistance of *n*-type GaN epilayers exposed to irradiation with MeV H, Li, C, and O ions is studied *in situ*. Results show that the threshold dose necessary for complete isolation linearly depends on the original free electron concentration and reciprocally depends on the number of atomic displacements produced by ion irradiation. Furthermore, such isolation is stable to rapid thermal annealing at temperatures up to 900 °C. In addition to providing a better understanding of the physical mechanisms responsible for electrical isolation, these results can be used for choosing implant conditions necessary for an effective electrical isolation of GaN-based devices. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1348306]

For the past decade, GaN and related compounds have been intensively studied due to their important practical applications in the fabrication of electronic and photonic devices. Indeed, GaN-based blue light-emitting diodes, blue lasers, UV detectors, and microwave power switches have been fabricated, stimulating significant research interest.[1,2]

Ion implantation plays an important role in the development of discrete devices and integrated circuits based on III–V compound semiconductors. Ion irradiation of III–V materials has a unique feature compared to irradiation of Si since it can convert conductive layers into highly resistive ones.[3] Selective masking of the semiconductor surface with photoresist followed by ion irradiation is a practical way to electrically isolate closely spaced devices. It is generally believed that trapping of carriers at deep centers associated with irradiation-produced damage (defect isolation) or with implanted species (chemical isolation) is the mechanism responsible for electrical isolation.[3]

Irradiation with keV ions has previously been applied for electrical isolation of GaN. However, the physical processes involved in this technological step are not completely understood at present. It has been shown that isolation which withstands thermal annealing at temperatures, at least, up to ~500 °C can be readily achieved by irradiation of GaN with keV H, He, N, O, Ti, Cr, or Fe ions.[4–8] However, in the case of keV ion implantation, implanted species stop inside the conductive GaN layer, and the damage profile is highly nonuniform throughout the GaN film. This makes the separation of the effects of defect and chemical isolation (and, therefore, the interpretation of data) difficult. Another problem of electrical isolation by keV ion bombardment is that many GaN-based devices are fabricated from quite thick ($\geqslant 1.5\ \mu$m) GaN epilayers. In this case, the achievement of adequate electrical isolation using conventional keV ion bombardment requires a large number of overlapping implants, which is undesirable.

In this letter, we study the formation of highly resistive layers in *n*-type GaN by MeV ion irradiation. In this case, projected ion ranges are greater than the thickness of GaN epilayers studied, and the profiles of generated atomic displacements are essentially uniform throughout the conductive GaN film. A single MeV implant, therefore, is sufficient to isolate a relatively thick GaN film. Moreover, irradiation with MeV ions has allowed us to separate the effects of defect isolation from chemical isolation and to avoid the formation of a layer with substantial defect-induced (hopping) conduction, which inevitably forms at the ion end-of-range region in the case of keV implants and usually complicates the interpretation of data.[3]

The *n*-type wurtzite GaN wafers used in this study were ~2 μm thick (~1.5 μm conductive layer over ~0.5 μm undoped GaN buffer), epitaxially grown on *c*-plane sapphire substrates by metalorganic chemical vapor deposition in a rotating disk reactor at the Ledex Corporation. Wafers with three different free electron concentrations, achieved by Si doping, were grown. The corresponding electrical characteristics of the wafers are shown in Table I.

Resistors of rectangular geometry cut from the above three GaN wafers were prepared. Ohmic contacts were formed by electron-beam evaporation of Ti/Al/Au (40 nm/120 nm/500 nm) and subsequent annealing at 900 °C for 30 s in an argon ambient at atmospheric pressure. Because the thickness of the contact layer was not sufficient to prevent the isolation of the underlying GaN regions by MeV light-

TABLE I. Original free electron concentration (n), effective Hall mobility (μ_{eff}), and sheet resistance (R_s) of the three GaN wafers used in this study.

Wafer	n (10^{17} cm^{-3})	μ_{eff} (cm^2 V^{-1} s^{-1})	R_s (Ω/sq)
I	3.0	570	218
II	23	350	92
III	56	330	37

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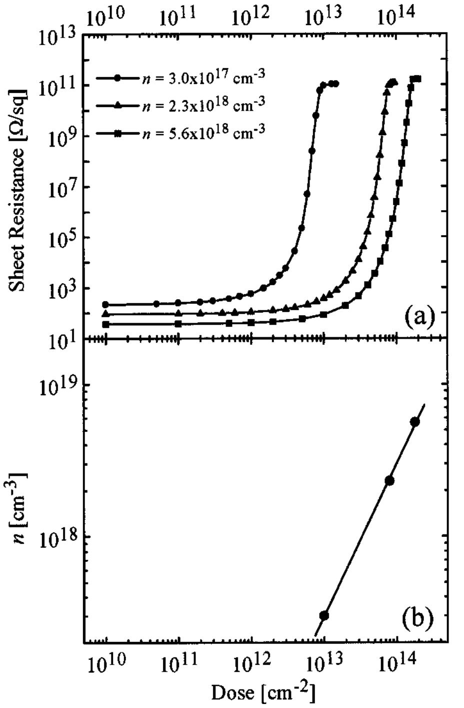

FIG. 1. (a) Dose dependence of sheet resistance of GaN samples irradiated with 6.6 MeV ^{12}C ions with a beam flux of $6.4\times10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Samples had different original free electron concentrations, as indicated in the legend. (b) The original free carrier concentration of the samples vs threshold doses obtained from data in (a). The straight line with a slope of 1.0, representing the best fit, is shown.

ion irradiation, additional masking with an aluminum foil of the contact regions was necessary.

These GaN resistors were irradiated at room temperature (RT) with 0.6 MeV ^{1}H, 3.0 MeV ^{7}Li, 6.6 MeV ^{12}C, and 6.6 MeV ^{16}O ions to doses in the range from 1×10^{10} to $2\times10^{15}\,\mathrm{cm}^{-2}$ using the ANU 1.7 MV tandem accelerator (NEC, 5SDH). Ion energies were chosen to place the damage peak in the sapphire substrate, beyond the GaN layer. During bombardment, samples were tilted by 7° off the surface normal direction to minimize channeling. Sheet resistance (R_s) was measured *in situ* after each dose step using a Keithley 619 electrometer.

Figure 1(a) shows the evolution of R_s of resistors with different original free electron concentrations (n) exposed to irradiation with 6.6 MeV C ions at RT. Figure 1(a) reveals that each of the curves has three distinct dose regions. The first region comprises the lowest doses, where R_s increases only slightly with increasing ion dose. The second region is characterized by a very fast increase in the value of R_s (by 9–10 orders of magnitude) in a relatively narrow dose interval. Such an increase in R_s is caused by the trapping of carriers at defects created by ion irradiation and damage-induced degradation of carrier mobility. A similar sharp increase in R_s has been observed in all the samples studied, but the dose interval where it occurs shifts to higher doses proportionally with n. Figure 1(a) also shows that, with further increasing ion dose, R_s values reach their highest levels after a certain dose has been accumulated (D_{th}—the so called threshold dose). The third dose region is for ion doses larger than D_{th}. With increasing ion dose above D_{th} and up to the maximum doses used in this work, the measured values of R_s remain approximately constant, forming a plateau. The levels of R_s at the plateaus shown in Fig. 1 are of the order of $1-2\times10^{11}\,\Omega/\mathrm{sq}$. However, the real maximum values of R_s of GaN layers are even larger since the R_s values measured have a contribution from the parasitic resistances of the experimental setup, which are of the same order of magnitude.

Figure 1(a) clearly shows that the dose dependence of R_s is not linear. A similar nonlinear dose dependence in GaN has previously been observed and explained by Uzan-Saguy and co-workers[7] based on a theory of electron transport in doped polycrystalline materials. However, this nonlinearity of R_s as a function of ion dose may be more simply explained. Indeed, in the first approximation, the concentration of deep traps, created by ion irradiation, linearly increases with dose, and, consequently, n will linearly decrease with ion dose. Therefore, the strong nonlinear dose dependence of R_s observed in Fig. 1(a) is not unexpected, taking into account that $R_s\propto1/n$. Moreover, with increasing number of traps in GaN, the concentration of charged scattering centers significantly increases, and electron mobility decreases, contributing to strong nonlinearity of R_s on ion dose. In addition, the real dose dependence of R_s may be more complex. For example, the concentration of deep traps may not increase linearly with dose due to complex defect interaction and dynamic annealing processes, as discussed in detail previously.[9]

In Fig. 1(b), the threshold doses of C ions [taken from Fig. 1(a)] are plotted versus the values of original free carrier concentration. Also shown in this Fig. 1(a) is a straight line fit with a slope of 1.0, which shows that D_{th} increases linearly with the original concentration of free carriers. This result may support (despite the complexity of the real defect processes taking place in GaN during ion bombardment) the above assumption that the dose dependence of n has a form of $n(D)=n(0)-A\times D$, where D is ion dose, $n(D)$ is free carrier concentration in the conductive layer after bombardment to dose D, and A is a constant which depends on ion mass and energy.

Figure 2(a) shows the evolution of R_s in identical resistors prepared from wafer I (see Table I) irradiated with 0.6 MeV H, 3.0 MeV Li, 6.6 MeV C, and 6.6 MeV O ions at RT.[10] It is seen that the curves progressively shift towards lower doses with increasing ion mass. This fact is related to the creation of a higher defect concentration in the conductive layer in the case of higher ion masses. In all the samples studied, R_s values reach their highest levels after D_{th} has been accumulated. Plotted in Fig. 2(b) is the number of atomic displacements (calculated using the TRIM code[11]) produced by the above four ion species in the conductive GaN layer versus the threshold doses. A straight line fit (with a slope of -1.0) shown in Fig. 2(b) demonstrates that the efficiency of carrier removal processes reciprocally depends on the number of atomic displacements.

These results show that ion doses required for an effective isolation of GaN have simple linear and reciprocal dependences on the values of initial free carrier concentration and ion-beam-produced atomic displacements, respectively. As a result, implant conditions necessary for an effective electrical isolation of a particular GaN-based device can be readily estimated based on experimental data presented here

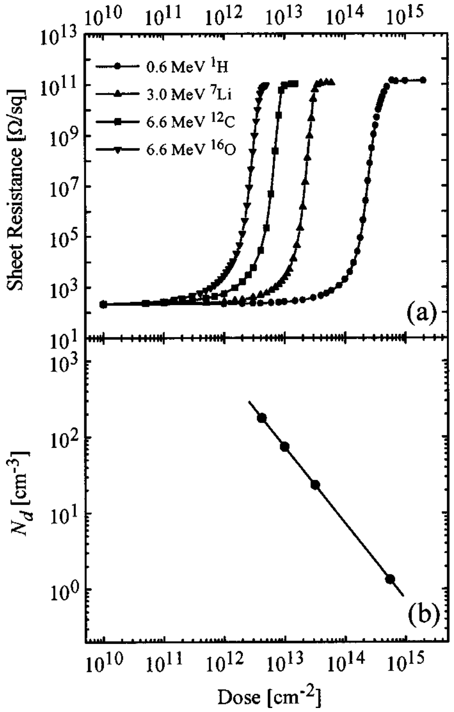

FIG. 2. (a) Dose dependence of sheet resistance in identical samples ($n = 3\times10^{17}\,\mathrm{cm}^{-3}$) for irradiation with different ions, as indicated in the legend. (b) The estimated concentration of atomic displacements (N_d) is plotted vs threshold doses obtained from data in (a). Also shown is a straight line with a slope -1.0 which represents the best fit to experimental data.

and the number of atomic displacements calculated using, for example, the TRIM code.[11] The technological application of ion bombardment for electrical isolation of GaN-based devices is also facilitated by very high thermal stability of such isolation. Indeed, in agreement with previous reports,[4,5] our data show that the samples irradiated to doses above D_{th} remain highly resistive after rapid thermal annealing at temperatures up to 900 °C, the maximum annealing temperature used in this study.

In summary, we have studied the electrical isolation of n-type GaN by MeV ion irradiation. Results show that sheet resistance of GaN layers increases up to $1-2\times10^{11}\,\Omega/\mathrm{sq}$ as a result of ion irradiation. The threshold dose (i.e., ion dose which is necessary to produce a concentration of effective deep level traps compared to the initial concentration of free carriers) linearly depends on initial free electron concentration and reciprocally depends on the number of atomic displacements produced in the GaN film. Based on these results, the threshold dose can be readily calculated from implant conditions. This study may, as a result, have significant technological implications for choosing implant conditions necessary for an effective electrical isolation of GaN epilayers by ion irradiation.

This work was partly supported by Conselho Nacional de Pesquisas (CNPq, Brazil) under Contract No. 200541/99-4.

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[10] At this stage, we cannot rule out the effects of beam flux on the efficiency of the production of lattice defects responsible for isolation. Therefore, beam flux values were chosen (3.9×10^{11} for H, 1.6×10^{11} for Li, 6.4×10^{10} for C, and $2.1\times10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for O ions) to keep the damage generation rate constant for irradiation with different species to suppress the influence of a possible dose rate effect.

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