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Electrical isolation of *n*-type GaAs layers by proton bombardment: Effects of the irradiation temperature

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The electrical isolation in *n*-type GaAs layers produced by proton irradiation at temperatures from −100 to 300 °C was investigated. The threshold dose for the isolation (D_{th}) was found almost identical for irradiation at temperatures from −100 to 220 °C. At 300 °C, a dose of ≅1.3 times higher is required for the isolation threshold. In samples irradiated to a dose of D_{th} at −100 °C or nominal room temperature, the isolation is maintained up to a temperature of ≈250 °C. In those samples irradiated at 300 °C it persists up to ≈350 °C. For doses of $3D_{\mathrm{th}}$ or above, the stability of the isolation is limited to temperatures of 450–650 °C, irrespective of the irradiation temperature (T_i). For practical applications where doses in excess to $5D_{\mathrm{th}}$ are usually employed, the irradiation temperature (from −100 to 300 °C) has only a minor effect on the formation and thermal stability of the electrical isolation. © *1998 American Institute of Physics.* [S0021-8979(98)03921-8]

I. INTRODUCTION

The ion implantation is a fundamental process for the development and fabrication of integrated circuits (ICs) and optoelectronic devices in silicon and compound semiconductor technologies. It is currently used to introduce dopant atoms in semiconductors in order to establish *n* or *p*-type conductive layers or to create specific damage distribution in the crystal subsurface layer. In the case of compound semiconductor technology, the implantation related damage is frequently employed to convert a conductive layer into a highly resistive one. This process is called implantation isolation or irradiation isolation.[1,2]

For electrical isolation purposes the irradiation is usually performed with light mass ions, such as H^+, He^+, B^+, O^+, etc. This assures a penetration depth comparable to or larger than that of the doped layers at the energies provided by the industrial implanters. The doses required for isolation are relatively low ($<10^{14}$ cm^{-2}), since tens or hundreds of carriers are removed per incident ion.

Current carriers are captured by damage related deep levels in the forbidden band gap.[3–9] When the trap concentration is high enough to capture all the carriers a conductive doped layer becomes electrically isolated.

It was previously inferred[10] that the defects responsible for carrier trapping in GaAs are the antisite defects and/or their related defect complexes, generated by the replacement collisions in the collision cascades.[11]

The thermal stability of the formed isolation is considered as the persistence of the sheet resistance (R_s) at a level typically higher than 10^9 Ω/□ after an annealing at a given temperature. It was determined previously that the thermal stability is a function of the ratio of the replacement collision concentration and the original sheet carrier concentration.[12–14] The upper temperature limit for which the isolation persists is ≅650 °C in irradiated *n*- or *p*-type layers.[14]

It was previously suggested that point defects, like vacancies and interstitials, may be involved in the thermal reactions which lead to the recovery of the electrical conductivity.[12] Since the dynamic annealing of point defects is a noticeable function of the sample temperature during irradiation (T_i),[15] it would be of interest to investigate the influence of T_i on the electrical properties of the irradiated layers. However, in spite of scientific and technological interest in this matter, a detailed study is still lacking in the literature.

In the present work, the effects of T_i on the isolation process in *n*-type GaAs layers were investigated systematically.

II. EXPERIMENTAL DETAILS

We used liquid encapsulated Czochralski (LEC) semi-insulating (SI) GaAs wafers of (100) orientation, having an *n*-type epitaxial surface layer. The epilayers are 0.32 μm thick and uniformly doped with silicon to the concentration of 1.5×10^{17} cm^{-3}. The original R_s of the epilayer is 580 Ω/□.

After cleaning with organic solvents the wafers were cleaved in pieces with dimension of 6 mm×3 mm in order to prepare rectangular resistors. The ohmic contacts to the resistors were formed by manually applying indium stripes (≅0.5 mm wide and ≅3 mm long) on the surface along the 3 mm long borders, followed by sintering at ≅200 °C for 2 min.

The resistors were irradiated with protons at an energy of 150 keV with the surface normal tilted 7° in respect to the beam incidence direction to minimize channeling effects.

The proton energy was chosen high enough to locate the peak of the deposited nuclear energy profile [1.13 μm, according to transport of ions in matter (TRIM)[16] simulation] far away from the epilayer/SI GaAs interface (0.32 μm). By

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adopting such a criterion, the number of replacement collisions per ion per unit depth length is almost constant along the epilayer.

The doped regions under the contacts were masked against the ion irradiation by the indium layers. Alternatively, in samples whose contacts were not prepared prior to the ion irradiation, the masking was provided by aluminum foils.

The samples received proton doses ranging from 1×10^{11} to 5×10^{15} cm^{-2} at -100 °C, at nominal room temperature (RT) of $\cong$20 °C, 165, 220, or 300 °C. The accuracy in the temperature control was of ± 3 °C.

A set of samples irradiated at -100 °C, RT and 300 °C was employed for the study of the annealing behavior of R_s. The chosen doses were experimentally determined to correspond to four different carrier trap concentrations. The lowest trap concentration is the one which just leads to the complete isolation. For the others trap concentrations, doses 3, 10 and 500 times higher than the ones required to attain the isolation were employed. Subsequently, isochronal annealing cycles were performed in a halogen lamp furnace at temperatures from 100 to 700 °C, for 60 s in argon atmosphere. The temperature of the silicon susceptor was controlled by a closed loop control system with an accuracy of ± 5 °C. Below 600 °C the annealing cycles accumulated in samples having ohmic contacts already prepared. At 600 °C or above, each resistor received only one anneal cycle, with the irradiated face in close contact with the silicon susceptor. Subsequently, the ohmic contacts were performed in these samples.

The R_s values were always measured using a 617 Keithley electrometer with the samples in the dark and at RT (unless otherwise noted).

III. RESULTS AND DISCUSSION

The evolution of R_s with accumulation of the dose is shown in Fig. 1 for T_i of -100 °C, RT, 165 °C, 220 °C, and 300 °C. The R_s values in the curve corresponding to T_i of -100 °C were obtained using one resistor for each dose. For any of the other T_i, the R_s measurements were performed during the dose accumulation in a specific resistor.

The sharp increase of $R_s$with the dose in the range from 4×10^{12} to 1.5×10^{13}cm^{-2} in Fig. 1 results form carrier trapping and mobility degradation.[12] The dose for which R_s reaches the highest level ($\cong 5 \times 10^9$ Ω/□) is labeled threshold dose for isolation (D_{th}). After irradiation to D_{th} practically all the carriers are captured by the traps. Further dose accumulation leads to the formation of a plateau in the curves. The residual conductivity in the plateaus is caused by the parallel conduction in the SI GaAs bulk material. The plateaus end when the damage concentration becomes high enough such that intradamage conduction starts to manifest.[17] Beyond this dose the conductivity increases due to the increase of the hopping conduction between the defects.

It is noticeable that D_{th} values are almost identical for T_i in the range from -100 to 220 °C [(0.9–1.0)$\times 10^{13}$ cm^{-2}], in spite of the strong temperature dependence of the dynamic annealing (see Fig. 1). The near coincidence of the D_{th} values for T_i in the range from RT to 220 °C in Fig. 1 demonstrates that the carrier trap structures are not noticeably influenced by the dynamic annealing, as pointed out in a previous publication.[10] In addition one may conclude that no significant annealing of the carrier traps occurs in the temperature range from RT to 220 °C.

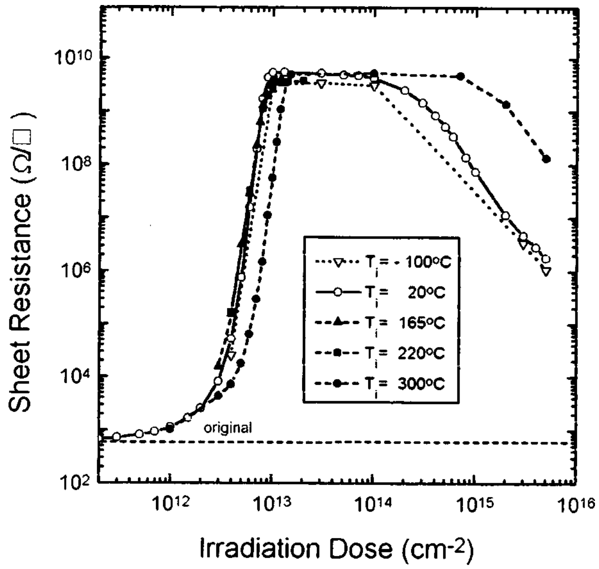

FIG. 1. Evolution of R_s with the dose accumulation in n-type epilayer resistors at temperatures from -100 to 300 °C. All R_s values were measured at RT.

By increasing T_i to 300 °C, D_{th} resulted in 1.3×10^{13} cm^{-2}, which is $\cong$30% higher than that after an irradiation at RT. Such an increase in the dose to attain the isolation at 300 °C is required for the replacement of the carrier traps which were annealed during the irradiation. This reasoning is based on a previous investigation which revealed the presence of a significant annealing stage of the carrier traps in the temperature range of $\approx$200–350 °C.[12]

The isolation formation at -100 °C was studied in further detail in a separate experiment in which the R_s measurements were performed at -100 °C. The results obtained are shown in curve (1) in Fig. 2. Curve (2) in Fig. 2 is a replot of the curve corresponding to T_i of -100 °C in Fig. 1. The R_s values in curve (2) were measured at RT. The higher D_{th} in curve (2) is clear evidence that a noticeable annealing of the carrier traps occurs in the temperature range from -100 °C to RT. Approximately 50% of the formed carrier traps at -100 °C are annealed out when the sample is warmed to RT. The higher R_s in the plateau of curve (1) is a consequence of the decrease of the bulk conductivity with the decrease of temperature.

Figures 3(a), 3(b), 3(c), and 3(d) show the evolution of R_s during subsequent thermal annealing for doses of 1, 3, 10, and 500 times, respectively, of the D_{th} values at the considered T_i. Curves (1), (2), and (3) correspond to T_i of -100 °C, RT, and 300 °C, respectively. For T_i of -100 °C or RT, the D_{th} is 1.0×10^{13} cm^{-2} and for 300 °C it is 1.3 $\times 10^{13}$ cm^{-2}.

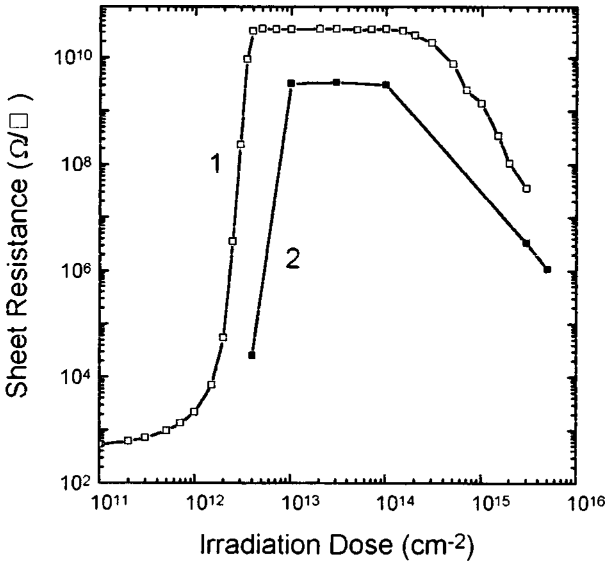

FIG. 2. Evolution of R_s with the dose accumulation at −100 °C. The R_s values were measured at −100 °C [curve (1)] or at RT [curve (2)].

In samples irradiated to D_{th} the annealing behavior of R_s is quite similar for T_i of −100 °C and RT [compare curves (1) and (2) in Fig. 3(a)]. One can conclude that the cold irradiation did not introduce any significant effect in the annealing behavior of R_s compared to that after RT irradiation. In agreement with a previous publication,[12] a recovery of the conductivity by 5 orders of magnitude is denoted in the temperature range of ≈200–350 °C. It was suggested that this annealing stage is promoted by annihilation of acceptor-like compensation centers.[12] The $\mathrm{Ga_{As}}$ antisites, which are double acceptors in GaAs,[18] probably recombine with V_{Ga} at temperatures above ≈200 °C.

It is interesting to note that the as-implanted R_s value (6×10^7 Ω/□) after irradiation at 300 °C to a dose of 1×10^{13} cm^{-2} (see Fig. 1) is more than three orders of magnitude higher than those obtained after an annealing at 300 °C in samples irradiated to the same dose, either at −100 °C (2×10^4 Ω/□) or at RT (3×10^4 Ω/□) [see curves (1) and (2) in Fig. 3(a)]. The isolation after irradiation at 300 °C is formed by carrier trapping at defect structures which are stable at least to 300 °C. This contrasts with the −100 °C or RT irradiation cases, for which remarkable trap annealing occurs at temperatures lower than 300 °C. These different thermal stabilities observed for the carrier traps indicate that different trap structures are generated according to the irradiation temperature. This fact was already reported by Stievenard *et al.*[6] for *n*-type GaAs layers irradiated with 1 MeV electrons at RT or at 300 °C, in which $E1-E5$ or $I1-I7$ traps, respectively, were observed.

By increasing the dose to $3D_{\mathrm{th}}$ the thermal stability increases up to 450 °C, irrespective of T_i [see Fig. 3(b)]. The recovery of the conductivity occurs via two annealing stages in samples irradiated at −100 °C or RT. The reverse annealing of the conductivity in the temperature range of 350–400 °C is clearly apparent in curve (1), weakly seen in curve (2), and absent in curve (3). The causes of the reverse annealing are still unclear. The second annealing stage starting at 450 °C recovers the conductivity by 5 order of magnitude, irrespective of T_i.

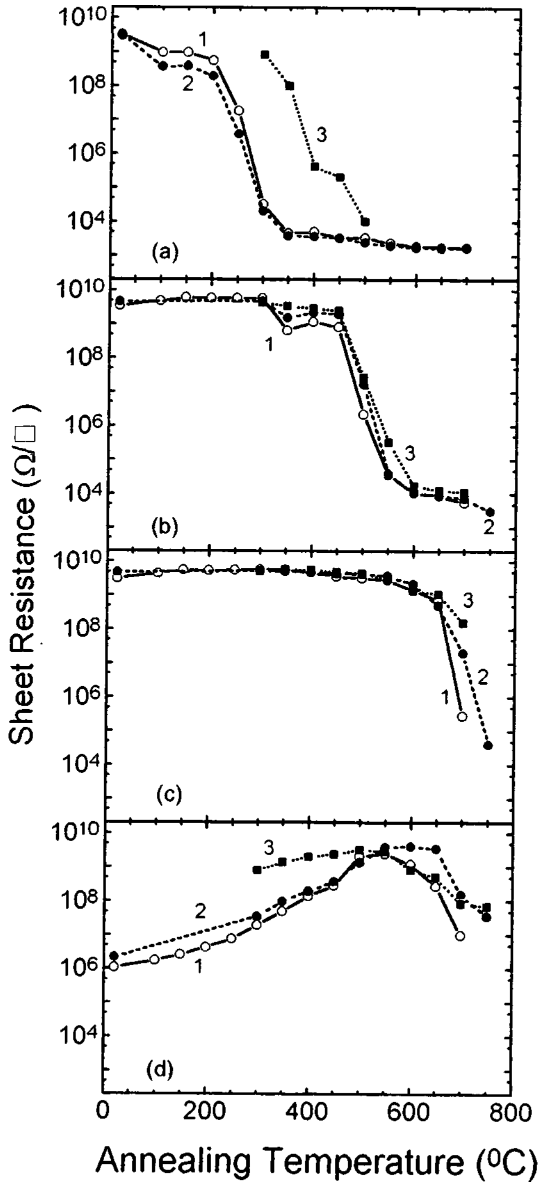

FIG. 3. Evolution of R_s during post-irradiation annealing in samples irradiated to the dose of D_{th} (a), $3D_{\mathrm{th}}$ (b), $10D_{\mathrm{th}}$ (c), and $500D_{\mathrm{th}}$ (d). Curves (1), (2), and (3) correspond to T_i of −100 °C, RT, and 300 °C, respectively. For T_i of −100 °C or RT D_{th} is 1×10^{13} cm^{-2} and for 300 °C it is 1.3×10^{13} cm^{-2}.

The annealing behavior of R_s in samples irradiated to $10D_{\mathrm{th}}$ resulted quite similarly for the three T_i cases [Fig. 3(c)]. The isolation is stable up to ≅650 °C. A sharp recovery of the conductivity occurs at temperatures above 650 °C. This annealing stage very likely corresponds to the dissolution of complex lattice defects formed in samples irradiated to high doses. It is known that temperatures in excess to 550 °C should be required to dissolve these defect complexes.[4] Vacancies very likely released from dissolution of complex defects participate in the reactions for the annihilation of the antisite defects.

The highest dose ($500D_{\mathrm{th}}$) corresponds to the case where hopping conduction is established in the as-irradiated samples. The increase of R_s with the increase of temperature in the range from 100 to 500 °C is caused by the reduction in hopping conduction due to the progressive annealing of the damage [see Fig. 3(d)]. In spite of the high proton dose used, there is no significant improvement in the thermal stability of the isolation compared to the $10D_{\mathrm{th}}$ cases for any of the T_i considered [compare Figs. 3(d) and 3(c)].

IV. SUMMARY AND CONCLUSIONS

In summary the isolation formation by proton irradiation in *n*-type GaAs layers at temperatures from −100 to 300 °C was systematically studied. It was found that the isolation is formed at doses which are quite similar for T_i from −100 to 220 °C. This result indicates the absence of any noticeable annealing of the carrier traps in the temperature range from RT to 220 °C. However, in the range from −100 °C to RT we observed that ≈50% of the formed traps at −100 °C were annealed out.

For T_i of 300 °C, a dose of 1.3 times higher than that at RT is required to form the isolation. This is understood considering that the traps were formed at a temperature which is within a range where a pronounced annealing stage of carrier trap structures is present.[12] The behavior of R_s with the annealing temperature was investigated for T_i of −100 °C, RT, and 300 °C. Similar annealing behavior of R_s observed in samples irradiated at T_i from −100 to 300 °C with doses $>3D_{\mathrm{th}}$ demonstrates that T_i is a parameter of weak influence on the annealing behavior of R_s.

Based on the results presented we conclude that in cases where the dose is made $\geqslant 5D_{\mathrm{th}}$ to obtain the maximum thermal stability of the isolation,[13,14] T_i can be varied in a wide range (−100–300 °C) without introducing any significant electrical effects.

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