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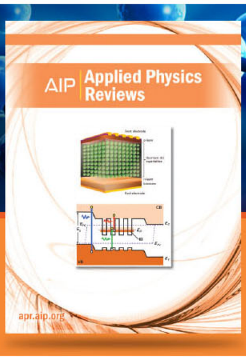

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Electrical isolation of $Al_xGa_{1-x}As$ by ion irradiation

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The evolution of sheet resistance R_s of *n*-type and *p*-type conductive $Al_xGa_{1-x}As$ layers ($x=0.3$, 0.6, and 1.0) during proton irradiation was investigated. The threshold dose D_{th} to convert a conductive layer to a highly resistive one is slightly different for *n*- and *p*-type samples with similar initial free carrier concentration and does not depend on the Al content. The thermal stability of the isolation, i.e., the temperature range for which the R_s is maintained at $\approx 10^9\ \Omega/\mathrm{sq}$, was found to be dependent on the ratio of the carrier trap concentration to the original carrier concentration. The thermal stability of isolated *p*-type samples is limited to temperatures lower than 450 °C. The temperature of ≈600 °C is the upper limit for the *n*-type samples thermal stability. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1427422]

AlGaAs–GaAs is one of the most widely used compound semiconductor structures for a broad range of device applications. High mobility of the electrons at the interface of modulation doped AlGaAs–GaAs heterostructures has led to the fabrication of high electron mobility transistors.[1] AlGaAs–GaAs structures are also widely used to fabricate heterojunction bipolar transistors[2] and various kind of lasers, from edge emitting lasers to vertical cavity surface emitting lasers.[3] There is much interest in multiple section lasers, which allow generation of picoseconds laser pulses.[4] For this purpose the carrier lifetime in the absorber section needs to be minimized. This could be achieved by introducing damage in the material, in order to create deep level centers and to decrease nonradiative lifetime. It is also necessary to electrically isolate the gain and absorber sections. Both these properties can be achieved by ion implantation. Proton and nitrogen bombardments of laser diode facets have been reported.[5]

Ion implantation is an essential process for the production of modern compound semiconductor devices and circuits and has been proven to be a successful method to convert a conductive layer into a highly resistive one.[6,7] Due to its simplicity, precise depth control, and compatibility with planar technologies, ion implantation is a potential alternative for mesa etching. Selective masking of the semiconductor surface with photoresist followed by ion irradiation is an efficient and practical way to isolate closely spaced devices.[8] The isolation of GaAs by ion irradiation has been studied intensively.[6–7,9–11] The isolation results from the trapping of free carriers by deep level centers that are not thermally ionized at device operating temperatures.

In this work, we study the formation of highly resistive layers by proton irradiation of *n*- and *p*-type $Al_xGa_{1-x}As$. It was shown that the threshold dose to convert a conductive layer to a highly resistive one and the thermal stability of irradiated AlGaAs do not depend on the Al content. 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 AlGaAs-based devices.

Semi-insulating VGF GaAs wafers of (100) orientation were used in this work. Epitaxial layers of 4 μm for *p*-type and 2 μm for *n*-type $Al_xGa_{1-x}As$ were grown using the ANU metalorganic chemical vapor deposition reactor. In order to prevent oxidation the samples were covered with a GaAs capped layer of 20 nm. Samples with Al content of $x=0.3$, 0.6, and 1.0 were grown. An electron concentration of $7.5\times10^{16}\ \mathrm{cm}^{-3}$ in the *n*-type samples was obtained by Si doping. The *p*-type doping was achieved by background carbon doping form the precursor trimethylaluminium. This resulted in different carrier concentrations for the *p*-type samples with an initial free carrier concentration of 3×10^{16}, 1.2×10^{17}, and $1.9\times10^{17}\ \mathrm{cm}^{-3}$ for $Al_{0.3}Ga_{0.7}As$, $Al_{0.6}Ga_{0.4}As$, and AlAs, respectively. This is mainly due to strong Al–C bonding, leading to increased incorporation of C with higher Al content layers.

The samples were cleaved in pieces of $6\times3\ \mathrm{mm}^2$ for the preparation of resistors. The ohmic contacts were performed by manually applying indium and sintering at ≈200 °C for 2 min. The prepared samples were irradiated with protons at an energy of 600 keV in the dose range of 1×10^{12}–$1\times10^{16}\ \mathrm{cm}^{-2}$. The ion current density was 62 nA/cm^2 and irradiation took place at room temperature. Implantation energy was chosen to place the damage peak in the GaAs substrate, generating a uniform defect profile along the AlGaAs layer depth. To minimize ion channeling the samples were tilted 15° off the surface normal direction. The sheet resistance R_s values were measured *in situ* after each irradiation step using a Keithley 617 electrometer.

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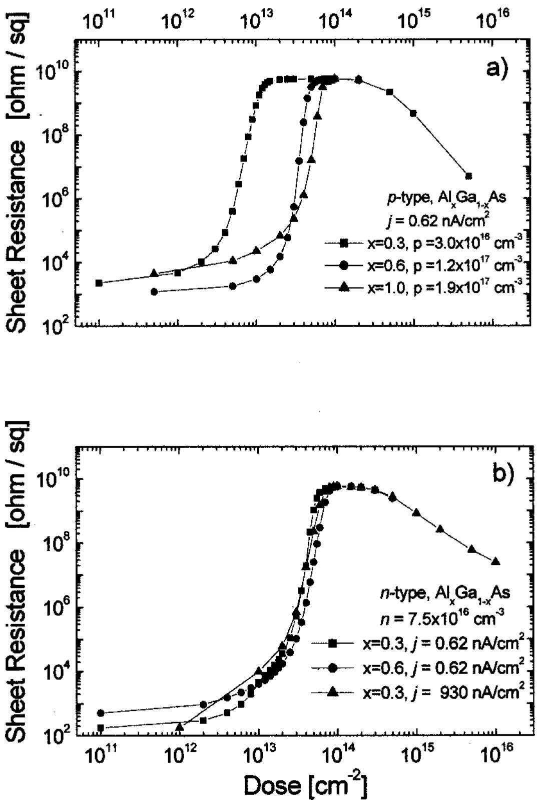

FIG. 1. Sheet resistance vs dose accumulation in *p*-type (a) and *n*-type (b) AlGaAs layers with different Al contents. The ion current density *j* and free carrier concentrations *n* or *p* are shown.

The implanted samples were subjected to rapid thermal annealing in the temperature range of 100–650 °C, for 60 s in an argon atmosphere. The annealing cycles were accumulated in the samples. The R_s was measured in the resistors at room temperature in the dark.

Figure 1(a) shows the evolution of R_s in *p*-type AlGaAs layers with the accumulation of the proton dose at the energy of 600 keV in resistors with different Al contents. During dose accumulation R_s increases as a consequence of carrier trapping and mobility degradation.[11]

The dose for which R_s reaches the maximum value ($\approx 5\times 10^9\ \Omega/\mathrm{sq}$) is hereafter called the threshold dose for isolation D_{th}. A similar sharp increase in R_s has been observed in all the samples, but the dose interval where it occurs shifts to higher doses proportionally with the initial free hole concentration p. It is interesting to mention that D_{th} depends linearly on the free carrier concentration but does not depend on the aluminum content of the samples. For doses equal to or higher than the threshold dose there are no free carriers in the doped layer. R_s saturates at its maximum value, which is determined by the electrical conduction through the underneath semi-insulating GaAs substrate. The current flows underneath and parallel to the isolated doped layer. The plateaus end when the damage concentration is high enough to permit carrier transport via hopping conduction. Further dose accumulation leads to a decrease of R_s due to an increase of hopping conduction.

Figure 1(b) shows the evolution of similar dose accumulation in resistors with different Al content of *n*-type layers. Similarly to *p*-type samples, the nondependence of the D_{th} on the aluminum contents is even more clearly seen here, due to the same initial free electron concentration of the samples. One resistor was irradiated with a much higher current density (930 nA/cm^2). Apparently, the threshold doses are found to be practically insensitive to the ion current density. The lack of influence of the beam current density signifies that the dynamic annealing does not play a role in the isolation process. After a careful analysis of the data in Fig. 1 one can conclude that the threshold dose to convert a conductive layer to a highly resistive one is slightly different for *n*- and *p*-type $Al_xGa_{1-x}As$ samples with similar initial free carrier concentrations and does not depend on the Al content.

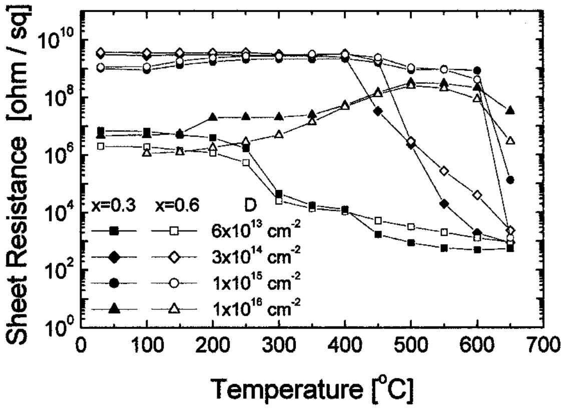

FIG. 2. Thermal stability of the proton beam isolated layers of *n*-type $Al_xGa_{1-x}As$ with $x=0.3$ and $x=0.6$, irradiated to different doses *D*.

It is interesting to compare these results with the previously published damage buildup data for $Al_xGa_{1-x}As$ of different Al compositions,[12] where the amorphization threshold increases with increasing Al content by more than 2 orders of magnitude. This is due to strong dynamic annealing behavior increasing the Al content. The nondependence of the threshold dose for isolation with the Al composition shows that the defects responsible for the free carrier trapping are special kinds of defects, very stable at room temperature. The natural candidates with these characteristics are antisite defects or complexes.

The thermal stability of the implanted samples was studied using doses from different regions of the isolation curves (See Fig. 1). The isolation is considered to be stable at a given temperature if R_s persists at $\approx 10^9\ \Omega/\mathrm{sq}$ after annealing at that temperature. Figure 2 presents evolution of R_s with the annealing temperature of the implanted *n*-type resistors using four different doses: $6\times 10^{13}\ \mathrm{cm}^{-2}$ (D_{th}); $3\times 10^{14}\ \mathrm{cm}^{-2}(5D_{\mathrm{th}})$; $1\times 10^{15}\ \mathrm{cm}^{-2}(17D_{\mathrm{th}})$, and $1\times 10^{16}\ \mathrm{cm}^{-2}(167D_{\mathrm{th}})$.

In the sample irradiated with the lowest dose ($6\times 10^{13}\ \mathrm{cm}^{-2}$), R_s starts to decrease at ≈250 °C. Increasing the dose to $3\times 10^{14}\ \mathrm{cm}^{-2}$ the isolation persists up to 400 °C. The conductivity is enhanced by about 5 orders of magnitude during annealing at 450–550 °C. In the sample irradiated to the dose of $1\times 10^{15}\ \mathrm{cm}^{-2}$ one can observe that the above mentioned annealing stages at $T<500\,°\mathrm{C}$ are absent. The isolation is stable up to 600 °C. After an irradiation to the dose of $1\times 10^{16}\ \mathrm{cm}^{-2}$, R_s is reduced to $\approx 10^7\ \Omega/\mathrm{sq}$ due to hopping conduction. A reverse annealing, i.e., the increase of R_s with annealing temperature, is observed in the temperature range of 100–500 °C. The improvement of isolation with temperature is explained by the progressive annealing

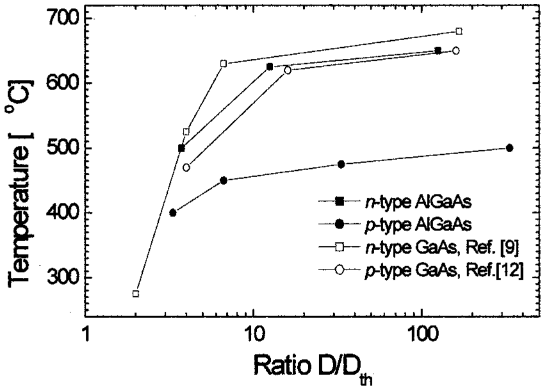

FIG. 3. Maximum temperature of thermal stability vs the ratio of irradiated dose to threshold dose.

of the damage, which progressively removes the hopping conduction.[10] After annealing at 600 °C the highest degree of isolation was obtained. It is interesting to note in Fig. 2 that resistors with different Al content ($x=0.3$ and 0.6) have similar temperature dependence for postirradiation annealing. Based on this result we may conclude that thermal stability does not depend on the Al content of the isolated layers. Similar results are obtained for *p*-type AlGaAs.

Figure 3 compares the maximum temperature of stability for isolated *n*- and *p*-type AlGaAs (this work) with isolated *n*[10] and *p*-type[13] GaAs. The general trend of this graph shows that the thermal stability increases with an increase in dose ratio. After a dose of $8D_{\mathrm{th}}$ the thermal stability saturated. Any further increase in dose does not increase the thermal stability significantly. For GaAs the temperature dependence is quite similar for *n*- and *p*-type resistors. However, there is a significant difference of about 150 °C in the maximum temperature of stability between *p*- and *n*-type AlGaAs. This result, although not fully understood and requiring further investigation, gives an indication that the electrons and holes are trapped by distinct defects with different thermal stability.

The evolution of the sheet resistance of conductive AlGaAs layers during proton irradiation and the stability of the formed isolation during postirradiation annealing were studied. The threshold dose to convert a conductive layer to a highly resistive one and the thermal stability of irradiated resistors do not depend on the Al content. The thermal stability of isolation was found to increase with the increase of the proton dose. To achieve maximum thermal stability (450 °C for *p*-type and 600 °C for *n*-type AlGaAs), the ratio between irradiated dose and threshold dose should be at least 8.

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