AIP | Applied Physics Letters

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Citation: Applied Physics Letters **75**, 1917 (1999); doi: 10.1063/1.124870
View online: http://dx.doi.org/10.1063/1.124870
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/75/13?ver=pdfcov
Published by the AIP Publishing

Electrical isolation of a silicon δ-doped layer in GaAs by ion irradiation

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(Received 8 March 1999; accepted for publication 29 July 1999)

The electrical isolation of a *n*-type δ-doped layer embedded into undoped GaAs was studied using proton or helium ion bombardment. The threshold dose for isolation D_{th} of the δ-doped layer was found to be ≈2 times higher than that predicted for thick doped layers of similar carrier concentration. The thermal stability of the isolation, i.e., the persistence of sheet resistance R_s at values $>10^9\,\Omega/\square$ after subsequent thermal annealing, is limited to temperatures below 400 °C. This temperature limit for the thermal stability T_{sm} is markedly lower than those observed in wider doped layers in which T_{sm} is ≅650 °C. A previously isolated δ-doped layer presents *p*-type conductivity after annealing at temperatures >600 °C . © *1999 American Institute of Physics.*
[S0003-6951(99)03639-6]

A semiconductor layer with a dopant distribution narrower than the carrier de Broglie wavelength is known as the δ-doped layer. The use of δ doping in the semiconductor device technology leads to significant improvements in the ultrahigh frequency and optoelectronic performance of the devices. Examples are the high transconductance GaAs-metal–semiconductor field effect transistors and the tunable GaAs laser using superlattices formed by alternated *n*-type and *p*-type δ-doped layers.[1]

The δ-doped layers are conveniently prepared by molecular beam epitaxy or metalorganic vapor phase epitaxy (MOVPE).[2] The extremely sharp dopant profiles are produced by interruption of the epitaxial crystal growth, deposition of dopant atoms on the semiconductor surface, and resuming the semiconductor growth. The temperature is usually lower than 700 °C to minimize thermal redistribution of the dopant profile. However, dopant profiles wider than a single monolayer may result in consequence of the presence of steps in the crystal surface during dopant deposition[1] and dopant diffusion during crystal growth. Another cause of redistribution is segregation of dopant atoms to the newly grown material with a constant three-dimensional density, closely corresponding to the solid solubility limit for the given growth temperature.[3]

Considering that δ-doped structures are potentially applicable to the development of electronic and optoelectronic devices and high performance integrated circuits, it seems to be of interest to investigate the electrical isolation formation in this structure. Up to now such study is lacking in the literature.

In the present work we discuss the isolation formation in the silicon δ-doped layer in GaAs, via light mass ion bombardment and the behavior of the sheet resistance recovery during postirradiation annealing cycles. We used samples having a layered epitaxial structure deposited on a semi-insulating (SI) liquid encapsulated Czochralski GaAs substrate of (100) orientation. The deposition method was the MOVPE performed in a horizontal reactor with $Ga(CH_3)_3$–AsH_3–SiH_4–H_2 gas sources at atmospheric pressure. First, an undoped GaAs epilayer with a thickness of 0.8 μm was deposited on the substrate and then the growth was suspended. Then SiH_4 was introduced in the reactor chamber for the deposition of Si dopant atoms. After the formation of the δ-profile of Si, the epitaxial growth was resumed for the deposition of a second undoped GaAs layer with a thickness of 0.13 μm. The temperature of the reactor was maintained in the range of 550–650 °C to minimize redistribution of the Si atom concentration profile.

Figure 1 shows the carrier concentration depth profile obtained from the capacitance-voltage (*C*-*V*) method. The peak electron concentration is 4×10^{17} cm^{-3} at the depth of 0.13 μm. The undoped layers presented residual *n*-type conductivity with carrier concentration of 1×10^{15} cm^{-3}, as denoted in Fig. 1 for depths below 0.45 μm. Electrical measurements in Van der Pauw devices[4] provided values of sheet resistance R_s, sheet electron concentration n_s, and effective

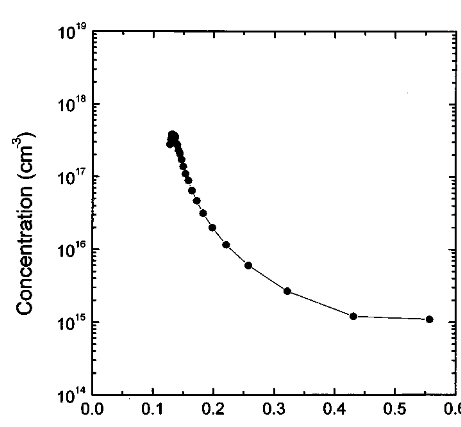

FIG. 1. Depth distribution of the electrons in the as-grown sample measured by the *C*-*V* method.

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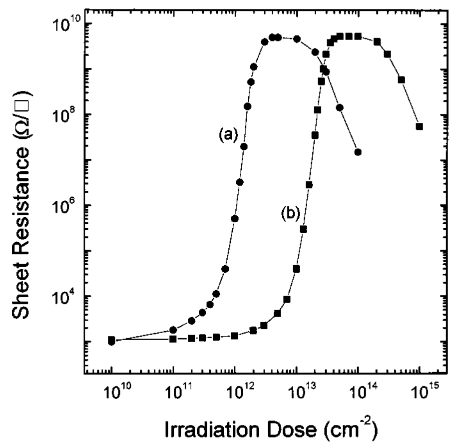

FIG. 2. Sheet resistance vs accumulated He^+ dose at the energy of 80 keV [curve (a)] and H^+ dose at the energy of 50 keV [curve (b)].

Hall mobility μ_{eff} of 1300 Ω/□, 1.65×10^{12} cm^{-2} and 2900 cm^2/V s, respectively.

The preparation and electrical characterization of the samples were realized at the Institute of Microstructure Physics of the Russian Academy of Sciences, at Nizhny Novgorod. The ion irradiation and annealing cycles were performed at the Physics Institute of Porto Alegre, Brazil.

Two type of devices were used in the ion irradiation experiments: rectangular resistors of 6 mm×3 mm and Van der Pauw devices of 6 mm×6 mm. The ohmic contacts to the devices were performed with indium, as described in detail elsewhere.[5]

All the ion bombardments were performed at nominal room temperature with $^1H^+$ at the energy of 50 keV or $^4He^+$ at 80 keV with the sample surface normal tilted 13° in respect to the beam incidence direction to minimize ion channeling effects. The ion energies were selected using TRIM[6] code simulation to place the peak of the deposited nuclear energy profile (0.39 μm) deeper than the depth of the δ-doped layer (0.13 μm) .

A set of resistors was submitted to H^+ or He^+ irradiation in accumulative dose steps. After each dose step the R_s value was measured without breaking the vacuum in the implantation chamber.

The results of this experiment are depicted in curves (a) and (b), respectively, of Fig. 2, for He^+ and H^+ irradiation cases. As the ion dose is accumulated an increase of R_s from its original value of 1.3×10^3 Ω/□ to a maximum of ≅5 $\times10^9$ Ω/□ was observed. The increase of the R_s results from carrier trapping at the irradiation damage centers and mobility degradation.[5] The threshold dose for isolation D_{th} was determined to be 4×10^{13} cm^{-2} for H^+ and 3×10^{12} cm^2 for He^+.

Further dose accumulation beyond D_{th} produces plateaus in the curves. The R_s values of the plateaus indicate complete isolation of the δ-doped and matrix layers, since it closely coincides with the sheet resistance of the SI GaAs substrate underneath. In each curve of Fig. 2, the plateau ends at a dose for which the damage concentration peak is high enough for the onset of the conduction via the hopping mechanism. Since the damage peak is located deeper than the δ-doped layer, the hopping conduction has no relationship with the conduction in the δ-doped layer. Further increase of the dose leads to a progressive decrease of R_s, as previously discussed.[5]

The pattern of the curves in Fig. 2 are quite similar to those observed for thicker doped layers (≅0.2 μm), doped either by ion implantation[5] or during epitaxial growth.[7] The shift toward lower doses of curve (a) in respect to curve (b) results from the higher nuclear energy deposited by He^+ compared to H^+.

The D_{th} values obtained in the δ-doped layer need further analysis. As inferred in a previous work,[8] the isolation formation is governed essentially by carrier trapping at the antisite defects and/or their related defect complexes formed by replacement collisions in the cascades. The densities of replacement collisions per incident ion n_r at the depth of the δ-doped layer estimated by TRIM[6] are 1×10^6 cm^{-1} for He^+ of 80 keV and 7×10^4 cm^{-1} for H^+ of 50 keV. The product $D_{th}n_r$ corresponds to the minimum volume concentrations of replacement collisions just necessary for trapping all the carriers in the δ-doped layer. Using the experimental values of D_{th} one obtains $D_{th}n_r$ of 3×10^{18} cm^{-3} and 2.8×10^{18} cm^{-3}, respectively, for He^+ and H^+ ion bombardments. Dividing these values by the peak carrier concentration (4×10^{17} cm^{-3}) one obtains 7.5 for He^+ and 7.0 for H^+. These are the numbers of replacement collisions required for the trapping of a single electron from the δ-doped layer. These values are ≈2 times higher than that required (3.1±1.2) for the isolation of implanted doped layers of similar peak carrier concentration.[9]

The discrepancies in the D_{th} values for thick doped[9] (0.2 μm) and δ-doped layers can be explained as follows. In the cases of much wider doped layers the carrier distribution closely coincides with the dopant distribution and there is charge neutrality along all the doped region. In the present case, the donor ions are confined within a layer thinner than the full width at the half maximum of the *C-V* profile (22 nm) while the electron profile spreads over a much wider region (see Fig. 1). Consequently, a space charge is present in the layer. Thus, even after trapping of all the electrons from the donors the space charge is still present, since the donor ions and the trapped electron distributions do not spatially coincide. Electron–hole pairs thermally generated within the space charge region should contribute to the reduction of the space charge. Those generated carriers which are not captured by the traps should contribute to the electrical conduction. Consequently, an additional dose has to be accumulated in the sample to enhance the trap concentration in order to attain the complete electrical isolation.

In another experiment resistors and Van der Pauw devices were irradiated with H^+ to doses of 2.0×10^{13} cm^{-2} ($0.5D_{th}$), 4.0×10^{13} cm^{-2} (D_{th}), 8.0×10^{13} cm^{-2} ($2D_{th}$), and 4.0×10^{14} cm^{-2} ($10D_{th}$). Subsequently, they were annealed in the temperature range from 100 to 700 °C in a halogen lamp furnace. The annealing cycles were conducted in argon atmosphere for a fixed time of 60 s. The experimental setup and annealing details were described elsewhere.[5]

Figure 3 presents the evolution of R_s in the resistors with the annealing temperature. The δ-doped structure irradiated to a dose $0.5D_{th}$ presents a monotone decrease of R_s with the annealing temperature in the range of 200–300 °C. A mini-

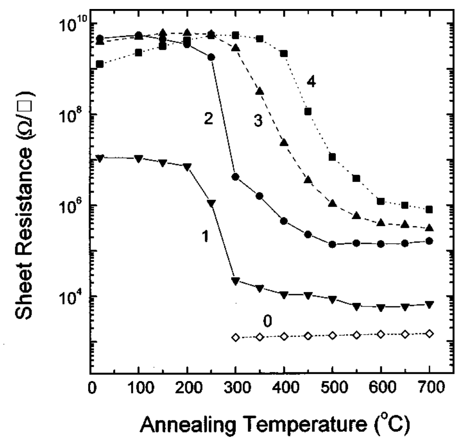

FIG. 3. Evolution of the sheet resistance with annealing temperature in samples irradiated with 50 keV protons to the doses of $0.5D_{th}$ (curve 1), D_{th} (curve 2), $2D_{th}$ (curve 3) and $10D_{th}$ (curve 4). Curve 0 represents the R_s evolution in a non irradiated sample. In our samples, D_{th} is 4×10^{13} cm^{-2} for H^+ irradiation at the energy of 50 keV.

mum R_s value of $\sim10^4$ Ω/□ is reached and it is maintained even after higher temperature annealing cycles (see curve 1 in Fig. 3). The sheet electron concentration returned close to the original value ($n_s\approx1.6\times10^{12}$ cm^{-2}), while μ_{eff} was maintained seriously degraded (560 cm^2/V s).

The temperature limit for the thermal stability T_{sm} increases with the increase of the ion dose. Here, T_{sm} is considered as the annealing temperature for which R_s decreases to 10^9 Ω/□. The values of T_{sm} are 250, 300, and 400 °C, respectively for the doses of D_{th} (curve 2), $2D_{th}$ (curve 3), and $10D_{th}$ (curve 4).

For the resistor irradiated to the dose of $10D_{th}$, a continuous increase of R_s in the temperature range of 100–300 °C is noticed (see curve 4). It is caused by the decrease in the hopping conduction by virtue of the damage annealing. The annealing of the trapping centers in the δ-doped layer manifests at temperatures above 350 °C.

An intriguing feature disclosed in the present study is the lower thermal stability of the isolation in the n-type δ-doped layer compared to that in ion-implanted or epitaxial thicker layers, for which the dopant profile is much wider. In this latter case, after irradiation to doses of $\geqslant10D_{th}$ the isolation persists even after annealing cycles at $\cong$650 °C,[5] which are 200–300 °C higher than in the δ-doped layer. This fact is not clearly understood at present.

Another interesting phenomenon is the convection from n-type to p-type conduction observed in structures irradiated to doses in excess of D_{th} and annealed at 600–700 °C. The final R_s values are in the range of 10^5–10^6 Ω/□ with a systematic increase of R_s with the irradiation dose (see curves 2, 3, and 4 in Fig. 3). The sheet hole concentration and μ_{eff} ranged from 0.35 to 1.8×10^{12} cm^{-2} and 25–95 cm^2/V s, respectively.

We argue that the conversion to p-type conduction may result after relocation of the Si atoms in δ-doped layers[10] from substitutional positions of the Ga sublattice to those of As sublattice assisted by As vacancies. Very likely, mechanical stresses present at the δ-layer/crystal interfaces should play a significant role in the stimulation of the process. One should point out that such type conversion is absent in implanted Si doped GaAs layers submitted to similar irradiation and annealing processes. Furthermore, nonirradiated δ-doped structures retain the n-type conduction up to the maximum experimented temperature of 700 °C. In this latter case, only a marginal increase of R_s by $\sim$20% is denoted (see curve 0 in Fig. 3).

In summary the electrical isolation of an n-type δ layer doped with silicon in GaAs was studied using H^+ and He^+ irradiation. The D_{th} values were found to be about two times higher than those predicted for an implanted or epitaxial layer of similar carrier concentration peak. This discrepancy is explained taking into account the lack of space charge neutrality along the δ-doped layer. Besides trapping all the carriers from the dopant atoms in the δ-doped layer, the space charge still persists. Due to the electric field present in the layer, thermally generated carriers accumulate over the layer and those carriers which were not trapped contribute to the electric conduction. This fact is reflected in a D_{th} higher than predicted for doped layers where space charge neutrality exists.

The thermal stability of the isolation was found to be restricted to temperatures below 400 °C, which is $\approx$250 °C lower than in wider doped layers. Furthermore, it was observed that the irradiated δ-doped layers present conversion from n-type to p-type conduction after annealing at 600–700 °C.

This work was partially supported by Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), and Conselho Nacional de Pesquisas (CNPq).

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