He^+- and Fe^+- ion bombardments in the electrical isolation of InP/InGaAs HBT Structures

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***Abstract* — We have investigated He^+- and Fe^+- ion bombardments in the electrical isolation of InP/InGaAs HBT and n-InGaAs structures. Single energy of He^+-ions were bombarded at room temperature whereas multi-energy Fe^+-ions were bombarded at 77K and room temperatures. At RT bombardment, maximum R_{sh} of $5x10^4$ Ω/sq and $8x10^4$ Ω/sq for He-ions whereas $1x10^5$ Ω/sq and ~10^6 Ω/sq for Fe-ions were obtained for the HBT and n-InGaAs structures, respectively. At 77K bombardment, an increase of over five orders of magnitude in R_{sh} (~$5x10^6$ Ω/sq) when compared to un-bombarded samples, which is very close to the intrinsic value for n-InGaAs (~$1x10^7$ Ω/sq). This is significantly higher than the RT bombardment results.**

I. Introduction

Device isolation by ion bombardment for GaAs-based III-V compounds has been extensively used for both microwave and optoelectronic devices. Ion bombardment is used to restrict current flow to active regions of the device, without having cross talk with other devices in the same wafer. They present various advantages, such as elimination of problems associated with step coverage, reduction in parasitic capacitance hence increasing transistor switching speed, and then conservation of planar structures geometry for high-frequency operation. Due to their wide-bandgap properties of GaAs-based materials, highly resistive regions of more than 10^8 Ω/sq are easily achievable, using light or heavy ion bombardment [1]-[6]. The application of this technique has been proven to be effective in the fabrication of microwave planar structure GaAs-based heterojunction bipolar transistors (HBTs) [6],[7].

However, it is more difficult to create highly resistive regions in InP and especially materials such as InGaAs. Since InGaAs is a narrow-bandgap material with a small bandgap (0.75eV at 300K) and a high intrinsic carrier concentration (n_i=$5x10^{11}cm^{-3}$), there is currently no effective bombardment technique available to electrically isolate the InGaAs-based devices. Maximum sheet resistance, R_{sh} of ~10^5 Ω/sq has been reported using He-ion bombardment in n-type InGaAs materials [8],[9]. In contrast, the isolation of p-type InGaAs material has been more successful. There have been reports that show maximum resistivity of 580Ωcm using light ion-bombardment [10]. There have also been attempts in using heavier ions such as Fe^+ to electrically isolate n-type InGaAs materials. Very high resistivity was reported using Fe^+-ions in n-type InGaAs material [11]. The major problem in the reported results is that the samples had to be annealed at very high annealing temperatures, which is undesirable for device fabrication. Since InP has similar bandgap (1.35eV at 300K) to that of GaAs (1.43eV at 300K), it is possible to achieve highly resistive regions of ~10^6 Ω/sq using either H^+ or O^+ -ion bombardment [12] and ≥ 10^7 Ω/sq using Fe^+-ion bombardment in n-type material [13]. Unlike Fe^+-ion bombardment for InGaAs material, a lower annealing temperature between 200 and 300°C was required to achieve maximum resistivity.

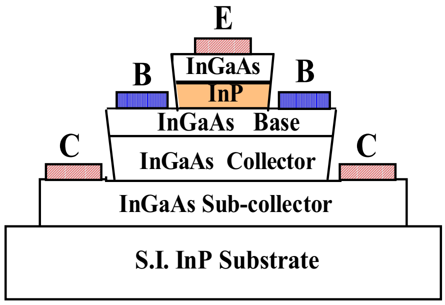

Fig. 1 A schematic diagram of a mesa structure InP/InGaAs HBT.

Achieving thermally stable high resistivity InGaAs layers at low annealing temperature is the prime objective in the fabrication of planar self-aligned InP/InGaAs HBT structures. There have been some reports on the electrical isolation of InGaAs layers but most of them were unable to achieve this criteria. Due to this, mesa etching remains the only available technique to fabricate InP/InGaAs HBTs, as shown in Fig. 1.

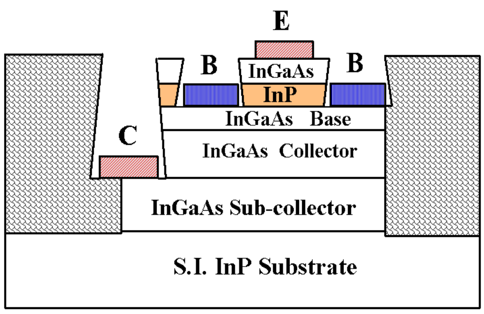

Fig. 2 A schematic diagram of a self-aligned planar structure InP/InGaAs HBT.

In this paper, we have demonstrated that highly resistive regions in the InP-based HBT layers can be obtained using cold Fe^+-ion implant isolation. This is very desirable for the design and fabrication of planar self-aligned InP/InGaAs HBTs, as depicted in Fig. 2.

II. Experimental Methods

Npn single HBT based on InP/InGaAs structure was grown by metal-organic chemical vapour deposition (MOCVD) on Fe-doped S.I. Substrate. The test structure has been reported elsewhere [9]. Another structure based on single layer n-type InGaAs material was used as a control sample during this experiment. Transmission Line Models (TLMs) were fabricated prior to bombardment on both the structures. This novel technique was used to measure sheet resistance (R_{sh}) of the bombarded region of the material [9].

Two sets of experiments were conducted. One involved single energy (600keV) bombardment of He^+-ions at room temperature (RT) and the other with multiple-energy (500keV + 2.0MeV) of Fe^+-ions at 77K and RT. Isolation of devices was achieved with a 2MV High Voltage Implanter. Samples were bombarded with surface titled by 7^o with respect to beam incidence direction to minimize ion channelling. Post implant annealing was performed by RTA in flowing nitrogen ambient, between temperatures of 50 and 500^{o}C. All measurements were conducted at room temperature.

III. Results And Discussion

To further understand the mechanism behind the damage created by ion species in an HBT structure, a simulation package known as TRIM (The Transport of Ions in Matter) was used [14].

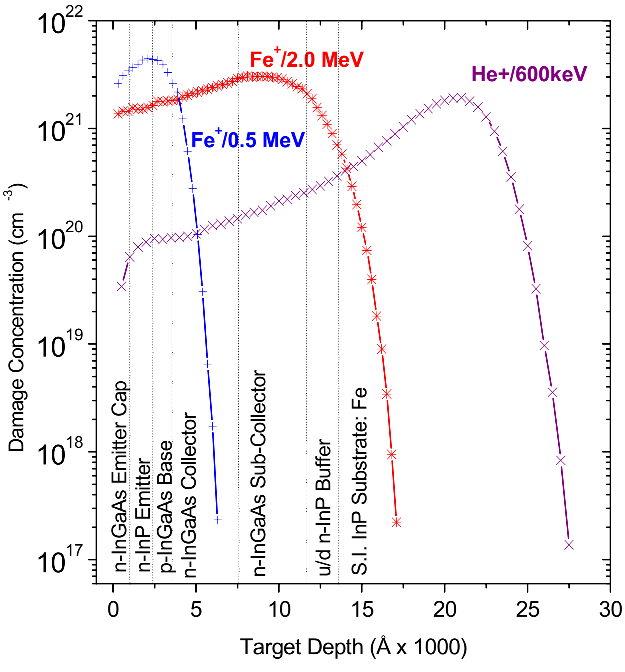

Fig. 3 Damage distribution for He^+ /600keV /3x10^{15}cm^{-2} and Fe^+ /500keV and 2.0MeV /1x10^{15}cm^{-2} -ions bombardments into InP/InGaAs HBT structure.

Fig. 3 shows the damage distribution of He^+ and Fe^+ -ions implanted into InP/InGaAs HBT structure. Single energy of 600keV was used for the He^+-ion bombardment so that the peak of the damage can be placed deep into the S.I. Substrate. Unfortunately, He^+-ion bombardment does not provide highly resistive regions in InGaAs layers, as will be shown later. In order to overcome this problem, multi-energy Fe^+-ions scheme was employed to achieve isolation throughout the full depth of the HBT structure (~1.5µm), as shown in Fig. 3.

A. Room Temperature Bombardment

Fig. 4 and 5 shows a comparison of R_{sh} as a function of annealing temperature in InP/InGaAs HBT structure and an n-type InGaAs (n=1x10^{18} cm^{-3}) following the bombardment of He^+ and Fe^+-ions at room temperature. In Fig. 4, the as-bombarded samples showed similar characteristics in R_{sh} by three orders of magnitude for both He^+ and Fe^+-ion bombardments when compared with their un-bombarded values of 28 Ω/sq.

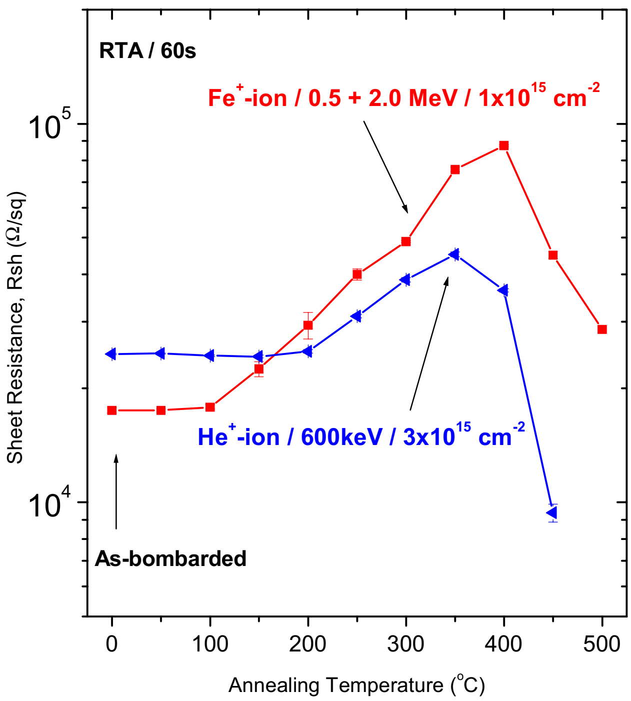

Fig. 4 Sheet resistance of the InP/InGaAs HBT structure after bombardment with He^+ and Fe^+ -ions bombarded at RT.

As can be seen in Fig. 4, R_{sh} increases with annealing temperature, as the density of implant-induced damage sites is reduced thus minimising hopping of trapped electrons from one site to another. Depending on dose, energy and ion species, R_{sh} reaches to a maximum at 350^{o}C for He^+-ions and at 400^{o}C for Fe^+-ions bombardment. Maximum R_{sh} recorded were 5x10^4 Ω/sq and 9x10^4 Ω/sq for He^+ and Fe^+ -ions , respectively. This is where most of the electrons are trapped, while hopping is at its minimum. Beyond the optimum annealing temperature, trapping density begins to fall below that of the electron and eventually returning to the initial R_{sh} of the material. The similarity observed in the HBT structure for RT bombardment for two types of ions may suggest that this was due to the effects of electric fields existing between the emitter-base and base-collector junctions, accelerating the migration of deep level traps and electron hoping in the damage region. Fig. 4 suggests that for RT bombardment, annealing characteristics for HBT structure is independent irrespective of ion species.

However, the evolution of R_{sh} with annealing temperature for Fe^+-ion bombardment in a single layer n-InGaAs at RT is different to that of the HBT structure, as depicted in Fig. 5.

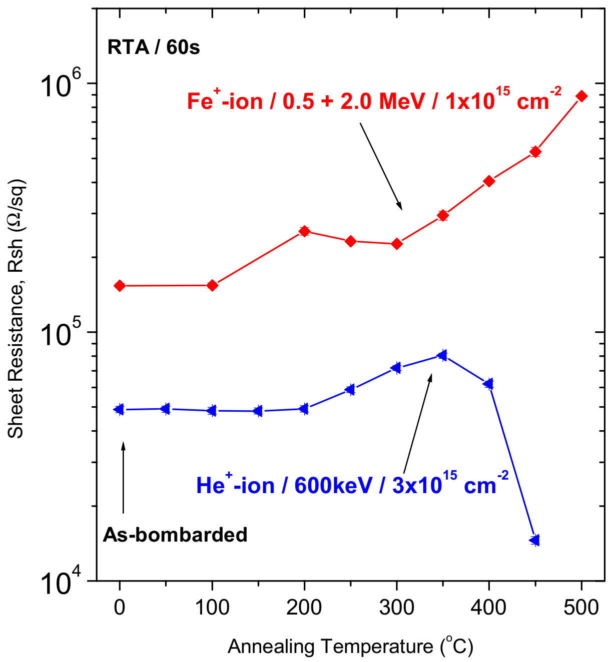

Fig. 5 Sheet resistance of the single layer n-InGaAs structure after He^+ and Fe^+ -ion bombardments at RT.

The evolution of R_{sh} for Fe^+-ion bombardment in n-InGaAs structure from Fig. 5 indicated that a maximum resistivity of $>10^6$ Ω/sq was achievable, provided a higher annealing temperature of >500°C was applied while the maximum R_{sh} for He^+-ions is only $8x10^4$ Ω/sq. Using the same He^+-ion bombardment recipe on a GaAs-based HBT structure, we were able to achieve R_{sh} as high as 10^8 Ω/sq [15]. Although the measured R_{sh} of $9x10^4$ Ω/sq achieved for RT bombardment with Fe^+-ions in HBT structure is relatively high, this is not adequate for effective device electrical isolation.

B. 77K Bombardment

Both HBT and single layer n-InGaAs structures were bombarded with multi-energy Fe^+-ion at 77K but measured at room temperature. A typical annealing characteristic is shown in Fig. 6. The samples bombarded with Fe^+-ions at 77K show some interesting characteristics: (1) The as-bombarded R_{sh} shows an increase of over five orders of magnitude (~$3x10^6$ Ω/sq) when compared to as-grown samples. This is significantly higher than the RT bombardment results, by a factor of more than 100, (2) The resistivity is high and thermally stable up to the annealing temperature of 200°C for the HBT structure and 250°C for the n-InGaAs structure, (3) Similar maximum R_{sh} of ~$4x10^6$ Ω/sq was achieved for both structures, (4) Maximum R_{sh} of ~$5x10^6$ Ω/sq was achieved after samples were annealed for half an hour at 200°C. This is greater than those previously reported in [8]-[12], (5) Increasing the annealing temperature beyond the respective optimum condition causes the resistivity to fall abruptly to ~$2x10^5$ Ω/sq before increasing again at 300°C, (6) The second recorded maximum R_{sh} of ~$1x10^6$ Ω/sq for the HBT structure occurs at 500°C, (7) Evolution of R_{sh} for n-InGaAs structure exhibits a similar trend to that of the HBT structure, and it is believed that the second maximum R_{sh} should occur in the same region.

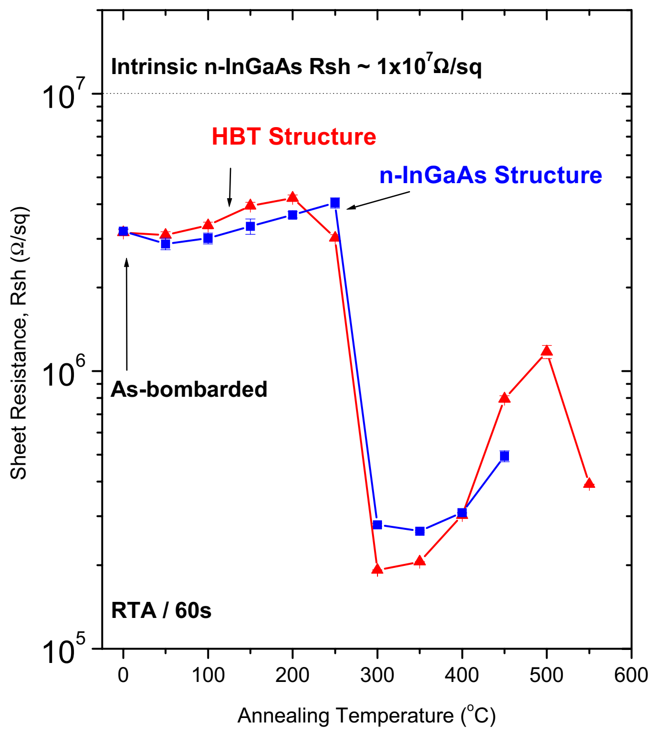

Fig. 6 Sheet resistance of InP/InGaAs HBT and n-type InGaAs structures after bombardment with (500keV+2.0MeV) Fe^+-ions at 77K.

It is interesting to note that the maximum R_{sh} recorded from this experiment is very close to the intrinsic value of n-InGaAs material ($1x10^7$ Ω/sq), as shown in Fig. 6.

Comparing Fig. 4 and 5 to that of Fig. 6 shows that the double peak behaviour that exists in the 77K bombardment may suggest the possibility of chemical-induced defects created by the Fe^+-ions at cold implant temperatures. The elements introduced by the chemical defects are stable up to a temperature of 200°C. These data clearly suggest that bombardment temperature plays a significant role in the creation of stable defects resulting in the isolation of narrow-bandgap InGaAs materials.

IV. Conclusion

We have shown that 77K Fe^{+}-ion bombardment produces a significantly higher and uniform electrical isolation in the InP/InGaAs HBT structure as compared to that of RT bombardment and He^{+}-ion bombardment. A maximum R_{sh} of $5x10^{6}$ Ω/sq is achieved for 77K Fe^{+}-ion bombardment which is close to the intrinsic value of n-InGaAs material (~$1x10^{7}$ Ω/sq). In addition the new results show that multi-energy Fe^{+}-ion bombardment produces thermally stable high resistivity at low annealing temperatures. To the best of our knowledge, this is the highest resistivity ever reported for the InP/InGaAs HBT structure.

Acknowledgement

This project is supported by the UK EPSRC. The authors wish to acknowledge the assistance and support of University of Surrey Ion Beam Facility, particularly Prof. B. Sealy, Dr. R. Gwilliam and Mr. P. Too.

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