Parallel Planar-Processed and Ion-Induced Electrically Isolated Future Generation AlGaN/GaN HEMT for Gas Sensing and Opto-Telecommunication Applications

S Ahmed1,2, S H Bokhari1, L A Khan2, F Amin1,2 and Z Hussain3
1Advanced Electronics Laboratory, Faculty of Engineering & Technology, International Islamic University, Islamabad - 44000, Pakistan.
2Centre for Emerging Sciences, Engineering & Technology, Islamabad-44000, Pakistan.
3Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA.
E-mail: ahmed.shuja@iiu.edu.pk

Abstract. Ion-implanted AlGaN/GaN High Electron Mobility Transistors (HEMT) devices were studied thoroughly to look into the possibilities of enhancing efficiency for high-power and high-frequency electronic and gas sensing applications. A dedicated experimental design was created in order to study the influence of the physical parameters in response to high energy (by virtue of in-situ beam heating due to highly energetic implantation) ion implantation to the active device regions in nitride HEMT structures. Disorder or damage created in the HEMT structure was then studied carefully with electrical characterization techniques such as Hall, I-V and G-V measurements. The evolution of the electrical characteristics affecting the high-power, high-frequency and ultra-high efficiency gas sensing operations were also analyzed by subjecting the HEMT active device regions to progressive time-temperature annealing cycles. Our suggested model can also provide a functional process engineering window to control the extent of 2D Electron mobility in AlGaN/GaN HEMT devices undergoing a full cycle of thermal impact (i.e. from a desirable conductive region to a highly compensated one).

1. Introduction
The semiconductor device needs to be doped with impurities to generate electrons in a specific region. However, this procedure may cause the free carriers to slow down because they end up colliding with the impurities residing in the same layer that were used to generate them in the first place [1, 2]. High Electron Mobility Transistor (HEMT) is a smart device that was designed to resolve this contradiction. HEMT accomplishes this by using high mobility electrons generated using the heterojunction of a highly doped n-type AlGaN thin layer and non-doped GaN layer [1]. HEMT, by virtue of its efficiency, is widely used as an extremely low noise device in terrestrial and space telecommunications systems, radio telescopes, Direct Broadcasting Satellite television (DBS) receivers, car navigation receivers, photonic sensing and ultra-high efficiency gas and PH sensors [1, 3].
Gallium nitride (GaN) based HEMTs excel over competing technologies for high power and high frequency applications [1, 3]. GaN HEMTs have an order of magnitude higher power density and higher efficiency than those of silicon (Si) and gallium arsenide (GaAs) transistors, allowing a ten time size reduction for the same output power, while simultaneously saving material cost [3]. The wide band gap of GaN allows for rugged high voltage and high-temperature sensing applications extensively covering both commercial and military markets [1, 3].

AlGaN/GaN HEMTs with varying source-gate spacing are usually fabricated using a standard technology process developed in various labs [3]. One such laboratory tested and commercially viable scheme [3] is intentionally chosen for our experiments to evaluate the designed process in our study. This HEMT structure is shown in figure 1 [3].

![HEMT Structure](image)

**Figure 1.** HEMT Structure (Commercially viable and Lab-scale qualified device: William J. Roman/NNIN IREU Site: Julich Forschungszentrum, Germany) [3]

The III-V semiconductors are currently employed in the fabrication of optoelectronic devices and integrated circuits (IC) for high frequency operations [4-16]. Electrical isolation of III–V semiconductors formed by introduction of a controlled concentration of point defects from light and heavy ion implantation is a well-established technique [6-16]. Besides the efficiency of this method to obtain highly isolated layers, it has the additional advantage of maintaining the planarity of the isolated structures [13-15]. Thermal processing of the crystal tends to remove ion beam induced damage and reduce the degree of compensation, while at the same time producing diffusion of the defect centers [8, 11-13]. Therefore thermal processing due to variable implantation temperature and post-implant annealing cycles is crucial to enable electrical and optical characteristics.

2. Experimental Conditions, Design and Details

The samples studied (test device is intentionally chosen to be of the same design as used commercially [3, Figure 1] to independently evaluate the influence of high energy implantation on AlGaN/GaN layers and subsequent impact on the physical properties important to enable sensing, frequency and power related device operations) were commercially grown by Metal Organic Chemical Vapor Deposition (MOCVD) on semi-insulating SiC substrate. The 2 Dimensional Electron Gas (2DEG) GaN channel was prepared with sheet carrier concentrations of $n_s = 3.1 \times 10^{13} / \text{cm}^2$ and $n_s = 3.1 \times 10^{14} / \text{cm}^2$. The ion implantation was carried out by Helium and Silicon ions irradiated at energy of 3000 KeV and 1000 KeV, respectively to place the peak of the damage distribution well inside the substrate as well as the GaN channel making an interface with the AlGaN barrier. A relatively flat damage distribution is created both in the top-layered GaN “cap” and AlGaN “barrier” so that a controlled amount of defects...
may be created at “interfaces” and “surface” for possible exploitation during the high power, high frequency and sensing applications. These implants were designed and modeled under the scope of this study and carried out at IBS Inc. USA with exact modeled parameters and dimensions. During implantation, the normal to the wafers was inclined at 15° with respect to the beam to minimize ion channeling. The selection of Helium and Silicon for damage studies for these HEMT test structures was crucial. Although the design studies included a range of ion species such as Zinc, Chlorine, Oxygen, Nitrogen etc. but the actual experiments were limited to one inert and lighter ion specie (Helium) and Silicon-a commonly used dopant in III-V devices. Silicon dopant is not known to create chemical impurity levels in AlGaN/GaN structures unlike Zinc, Chlorine, Oxygen and Nitrogen etc. The in-situ thermal effects caused by relatively high energy implantation due to beam heating and self-annealing of defects in HEMT devices were suspected to play an important role in affecting the device characteristics. Isolation implants were performed at different combined doses ranging from $5 \times 10^{13}$ cm$^{-2}$ to $2 \times 10^{15}$ cm$^{-2}$ at room temperature (RT). The doped regions under the contact areas were masked using the metal foil on top of those contacts. The resistivity and Hall measurements were carried out using Ecopia HMS3000 system, whereas HP 4156 parameter analyzer was used to evaluate the DC characteristics. Some of the measurements, implant schedules and annealing cycles were repeated and double checked at facilities in Berkeley National Laboratory, USA.

3. Results, Analysis and Discussion

Utilizing the similar model as devised in reference 17, we conducted a very similar experiment to qualify the threshold dose model for III-N-V devices. Following reference 14, 16 and 17, a threshold dose for isolation, $D_{th}$, can be defined as the minimum ion dose at which sheet resistivity, $R_s$, reaches its maximum value. The presence of threshold doses can easily be observed in Fig. 2, where two distinct threshold doses exist for two different initial sheet carrier concentrations of GaN layers. It has already been demonstrated [14, 16, 17-20] that ion doses required for an effective isolation of GaAs devices have

![Figure 2. Evolution of sheet resistance with the increasing ion dose (experiments designed as similar as depicted in Reference 17 to qualify the model requirements)](image-url)
simple linear and reciprocal dependences on the values of initial free carrier concentration and ion-beam-produced atomic displacements, respectively. If $n_{so}$ is the original sheet carrier concentration of the n-type GaN layers, $D$ is the implanted dose to isolate the structure, $n_{sD}$ is the measured sheet carrier concentration after the isolation implantation to dose $D$ then $R$ will be the carrier removal rate which is a function of mass and energy of the ion. The equation relating these parameters is as follows [17]:

$$n_{so} = n_{sD} + RxD$$

(1)

Since we do not intend to fully compensate the layers, optimum carrier removal rate is not considered while designing these experiments. The modelled parameters (using the Monte Carlo simulator called Stopping and Range of Ions in Matter [2] and SUSPRE) in terms of accumulated disorder and energy loss due to electronic and nuclear stopping are summarized in Table 1 for each case.

Table 1. The modelled physical parameters in response to the high energy ion implantation to the active device regions in nitride HEMT structure

| PHYSICAL PARAMETERS | 3000 KeV He$^+$ into SiC at $R_p$ (10.7 microns) | 3000 KeV He$^+$ into GaN Channel (3 microns) | 1000 KeV Si$^+$ into GaN Channel at $R_p$ (1.45 microns) |
|---------------------|-----------------------------------------------|-------------------------------------------|---------------------------------------------------|
| Energy loss due to Electronic Deposition (electron volt/angstrom) | 11.98 | 23 | 14.88 |
| Energy loss due to Nuclear Deposition (electron volt/angstrom) | 0.19 | 2.46 | 21 |
| Accumulated Disorder % | 7.3 | 1.9 | 15.1 |

The threshold doses in this experiments are $D = 2 \times 10^{14} \text{ cm}^2$ and $D = 2 \times 10^{15} \text{ cm}^2$ for the n-type GaN layers with initial channel sheet carrier concentrations of $3.1 \times 10^{13}/\text{cm}^2$ and $3.1 \times 10^{14}/\text{cm}^2$, respectively. Figures 3 and 4 illustrate the isolation characteristics (resistivity) for different starting material layers implanted with combined implantation at RT for a range of doses including the threshold doses in each case. Each data point is comprised of the cumulative isochronal annealing sequence for 50s period. For the $D_{th}$ case in Figure 3, the stability of the isolation is restricted to temperatures below 400 °C. In the samples irradiated to doses higher than the threshold dose ($2.5D_{th}$) the isolation persists up to the temperature of 350 °C. The increase of the irradiation dose to $10D_{th}$ leads to the decrease of $R$, because of hopping conduction in the highly damaged region. During post irradiation annealing there is a progressive increase of $R$, with increasing temperature up to 300 °C, since the carrier hopping becomes less effective as the damage is repaired. The defects are removed by annealing above this temperature, which would correspond to the annealing of defect clusters or defect complexes, as already observed and reported in cases such as experiments done in reference 17 and corresponding references therein.
Figure 3. Carrier Removal characteristics (sheet resistance versus post-implant annealing temperature) for AlGaN/GaN device structures of initial sheet carrier concentration of $3.1 \times 10^{13} \text{ cm}^{-2}$ in GaN channel.

Figure 4 also explains that the devices of starting material with high sheet channel carrier concentration are reasonably isolated with threshold doses. Further higher doses, for example in the case of Figure 3, are not needed to obtain better isolation. The larger thermally stable window (till 500°C) achieved in the case of the results shown in figure 4, is sufficient for subsequent processing such as contact sintering. The evolution of sheet resistivity with varying annealing temperatures at certain ion fluence (variable doses with respect to the already calculated threshold doses in Figure 2) shown in Figures 3 and 4 follow the similar trend and behave almost identically to a similar finding in case of GaAs layers isolated with protons [20]. This is expected as the post-implant-annealed-isolation trends are reported to behave in a similar fashion for most of the III-V devices, particularly for damage-only ion species such as protons, helium and silicon [6-15, 20]. As part of our study, we aimed to employ the technique of ion beam engineering onto the scheme of commercially designed AlGaN/GaN HEMT structures. While using the modelled parameter of threshold dose during the ion implantation, it is experimentally shown above that one can make the layers highly resistive and hence the extent of mobile electrons can be reduced according to the requirements of the device operations. One can achieve a fully compensated layer either in capped layer, barrier layer, channel, buffer or substrate. The design and modelling of ion implantation parameters, such as in our experiments, provide us a flexibility to control the amount of mobile carriers within a certain layer or interface, which may in turn be utilized to control the high-power and high-frequency operations. The usage of high energy implantation (particularly the MeV range of incident energies) is known to produce special defect complexes due to the dynamic annealing during the process of implantation. Therefore, such thermal effects also contribute in the significant results achieved after the implantation in form of physical changes experienced by the lattice. With the scope of high electron mobility transistor’s operation in mind, our proposed design of ion
implantation parameters also provide an effective solution to improve the efficiency of device characteristics.

Figure 4. Presence of persistent electrical compensation: thermally stable process window for combined Helium and Silicon Implantation-compensated AlGaN/GaN device structures of initial sheet carrier concentration of 3.1x10^{14} cm^{-2} in GaN channel. These structures are implant-isolated at RT for a range of doses including the threshold doses in each case. Each data point is comprised of the cumulative isochronal annealing sequence for 50s period.

Being used in RF/Microwave amplification environment, nitride HEMT devices are considered to have efficiencies to operate both in low and high field carrier transport. This demands a high carrier density along with high carrier mobility even during the relatively high temperature environments. Persistent low sheet resistivity and high 2DEG mobility is desirable physical attribute of such devices. This can be only achieved if we fabricate the HEMT structure with (a) high spatially distributed conductivity of GaN channel, and (b) high quality of AlGaN/GaN interface. The higher strain and better carrier confinement on AlGaN/GaN interface may provide a desirable quality lower sheet resistivity as well as higher 2DEG mobility.

We suggest that by using the high energy ion implantation with a uniformly distributed damage distribution in the capped layer (near surface regions) and peak of the damage profile within the channel with a reasonable extent of damage therein may create such defects within the lattice which may confine the carriers at the interface effectively. The follow-up annealing at a certain temperature, while recovering the lattice after ion irradiation, may release an additional amount of the trapped carriers in the channel which in turn would raise the mobility of the electron gas. Ion implanted structures may consequently exhibit better output device characteristics by virtue of getting damaged to an extent where they form
defects which help the interface relax in such a manner that while undergoing the reversal effect (annealing to recover the ion-induced damage) they provide more carriers to the channel with greater mobility and lower sheet resistivity. This way, relatively higher initial carrier density materials may also be used to perform device operations exactly the same way as could be done with lower initial carrier densities in AlGaN/GaN structures. Therefore, our suggested ion implantation model and designed experiments provide a substantial control on the carrier transport mechanisms while looking at the output device characteristics of AlGaN/GaN HEMT structures. This discussion is exhibited in Figure 5, where initial sheet carrier concentration is plotted against the 2DEG hall mobility in AlGaN/GaN layers for HEMT structures with and without implantation. The samples which were irradiated with combined implantation schedule of Helium and Silicon ions, received the fluence which was at least two orders of magnitude below the threshold doses that were used in earlier experiments for each independent case of initial sheet carrier concentration. This is due to the fact to produce light damage in the lattice which is neither stable nor long range to compensate the layer fully. This is an extent of ion-induced damage which is just about sufficient to trap the carriers at interface and recoverable at a low thermal budget. Figure 6 clearly shows that the higher values of 2DEG mobility are achieved when the HEMT structures have undergone a carefully designed ion implantation and annealing at temperatures around 400°C. This trend is repeatable for starting materials with different initial carrier densities.

![Figure 5. 2DEG Hall mobility versus initial channel carrier density (n_s = 3.1x10^{13} cm^{-2} and n_s = 3.1x10^{14} cm^{-2}) for AlGaN/GaN structures with and without ion implantation and annealing cycles (combined He^{-} and Si^{-} implants with ion doses 2 orders of magnitude lesser than the Threshold Dose in each case as shown in Fig.2)](image)

A converse is plotted in Figure 6 where sheet resistivity is plotted against the starting carrier density of AlGaN/GaN HEMT structure for cases where the structures are measured with and without the ion irradiation received. A converse pattern is achieved as compared to Figure 5. It is interesting to note that the lattice engineering due to the carefully designed ion implantation schedule and subsequent rapid thermal annealing provided a very low value of sheet resistivity (∼100 ohms/square) which is better than many commercial devices manufactured by conventional process routines without introducing lattice normalization engineering by ion implantation.
Figure 6. Sheet Resistivity versus initial channel carrier density ($n_s = 3.1 \times 10^{13}$ cm$^{-2}$ and $n_s = 3.1 \times 10^{14}$ cm$^{-2}$) for AlGaN/GaN structures with and without ion implantation and annealing cycles (combined He$^+$ and Si$^+$ implants with ion doses 2 orders of magnitude lesser than the Threshold Dose in each case as shown in Figure 2).

Figure 7. Characteristic trends of extrinsic transconductance ($G_m$) and drain current density ($I_{DS}$) versus the gate voltage ($V_g$).

Both the lower values of sheet resistivity and higher value of 2DEG mobility are vital to improve the RF characteristics of the HEMT device for small signal applications. Figure 7 exhibits the characteristic trends of extrinsic transconductance ($G_m$) and drain current density ($I_{DS}$) versus the gate voltage ($V_g$). The
measurements were performed with the $V_{DS} = 5$ Volts supplied to the structure having gate dimensions of $\sim 0.4 \times 220 \ \mu m^2$. A maximum value transconductance of over 300 mS/mm was achieved for ion-implanted structures, which is better than the average commercial HEMT structure without undergoing the post process ion implantation and annealing cycles.

4. Conclusion
The ion implanted AlGaN/GaN High Electron Mobility Transistors (HEMT) test structures were studied thoroughly to look into the possibilities of enhancing the HEMT efficiency for high-power and high-frequency electronic, photonic and gas sensing applications. With the results of this detailed study, we conclude the following:

- A dedicated experimental design was created in order to study the influence of the physical parameters in response to the high energy (by virtue of in-situ beam heating due to highly energetic implantation) ion implantation to the active device regions in nitride HEMT structures. Several sets of simulations were performed to predict the appropriate experimental conditions during the process of ion implantation induced damage formation before the test structure actually undergone the ion irradiation. A very calculated disorder or damage created in the HEMT structure was then studied carefully with Electrical characterization techniques such as Hall, I-V and G-V measurements.

- The evolution of the electrical characteristics affecting the high-power and high-frequency operations was also analyzed by subjecting the HEMT active device regions to the progressive time-temperature annealing cycles.

- The influence of relatively damaged HEMT structure by using “carefully” designed ion irradiation protocols was compared with the ones which are commercially available (having no post-process implantation protocols experimented) and it revealed that by changing the ion-induced physical dynamics of the channel and interface regions in AlGaN/GaN HEMT structures may enhance the operational efficiency of the device in many ways.

- The suggested model can also provide a functional process window to control the extent of 2D Electron mobility in the AlGaN/GaN HEMT devices undergoing a full cycle of thermal impact i-e from a desirable conductive region to a highly compensated one. That is shown possible by engineering the HEMT structures with or without the irradiation of so-called Threshold Doses ($D_{th}$) and their consequent impact on the carrier density of the channel in the AlGaN/GaN HEMT devices. The evolution of such a physical impact is also studied by varying the annealing temperatures to devise process instruments for various operational domains in AlGaN/GaN HEMT structures. These results and analysis have ramifications for HEMT device design and fabrication process protocols in the manufacturing of opto-telecommunication components and ultra-high efficiency gas sensors.

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