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Refined isolation techniques for GaN-based high electron mobility transistors

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ABSTRACT

This work investigates the Ar^+/N^+ based ion implantation and Ar based reactive ion etching (RIE) techniques for device isolation. A comparison of ion implantation technique with three ion energies (20/35/65 keV) and 4 energies (20/35/65/160 keV) of Ar^+ and N^+ with different ion doses for isolation was reported. Use of 4 energy ion implantation provided better isolation. Ar based single and dual step reactive ion etching process was also explored for the mesa isolation of GaN HEMTs. The etch rate increases (44.7%) significantly after mixing of Ar gas directly with BCl_3: Cl_2 combination. Hence, the Ar addition in the single step etching proved to be more beneficial as compared to the double step etching technique.

1. Introduction

AlGaN/ GaN high electron mobility transistors (HEMT) devices are the incredible contender for the cutting edge power, voltage, microwave, optoelectronics, and biosensing devices due to the magnificent combination of large band-gap, high electron mobility, high carrier concentration, high saturation velocity with high electric field value [1–6]. High transconductance and high sensitivity are required for biosensing application which can be accomplished via trimming down gate to channel distance. Gate recess is a well-known and an immediate technique of increasing the device transconductance (g_m) [7]. However, gate recess provides drastic reduction in drain current (I_{ds}). So as an alternative method we can use thin AlGaN structure to trim down gate to channel distance. In this study, we used 18 nm thin AlGaN as a barrier layer. Nevertheless, in order to get proficient usage of the distinct III-Nitride hetero structure properties in HEMT technology, various device processing steps must be expounded. Device isolation is one of the most important process step attained by using mesa etching or ion implantation technique [8].

Inter-device isolation in GaN HEMT is mostly exercised by creating mesa structures utilizing dry etch process. Lamentably, the chemical inertness of nitride material diminishes the etch rates. Due to which, the ratio combination of chemical radicals with ions utilized as a part of dry etching technique (RIE) is by all accounts feasible innovation to evacuate materials faster, than conventional wet etching process. Drawbacks of these mesa processes are related to mesa sidewall. This sidewall may prompt to additional gate leakage current and lessened breakdown voltages [9]. Various methodologies were addressed to take out issues related to the mesa sidewall. Authors in [10] revealed an oxide-filled isolation configuration to cover the mesa edge and diminish related gate leakage current [11]. Besides, planar ion implantation (I.I) approaches to avoid the mesa sidewall and lessen step coverage problem in the gate at mesa edge, thus reduces the gate leakage current and improve the yield and uniformity [12–14]. Implant isolations can be accomplished in GaN utilizing H^+, He^+, N^+, F^+, Mg^+, and Ar^+ ions [15–25]. The heavy Ion mass (Ar+) isolation implantation created the displacements at the shallower location with a higher concentration compared to light atomic mass ions (i.e., H+, He+ or N+). A heavy ion is expected to introduce more lattice damage and disorders and thus it is able to withstand subsequent high temperature processes. The lower implantation incident energy decreases the probability of surface damage of the device and increases the yield. The multiple incident ion energy and multiple ion dosage for two different ion masses were used and compared to ensure high-quality isolation in both AlGaN and GaN buffer layers with good thermal stability. To the best of author's knowledge till date, the previous writings offer no such direct multi-parametric performance evaluation involving these device isolation techniques. This work addresses comparative investigation of device performance on fabricated HEMTs by mesa etch and ion implantation.

This work firstly exhibits the device isolation using ion implantation technique. Two different ion species (Ar^+ and N^+) with multiple-energy and multi-dosage are employed in this process. Furthermore, we

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give an account of electrical studies made on AlGaN/GaN HEMTs utilizing RIE for mesa etching. Ar^+ based chemistry is used in single and double step RIE process for Mesa isolation of GaN HEMTs.

2. Experimental details

The AlGaN/GaN HEMTs structure used for the experiment consisted of 2 nm AlN nucleation layer, along with 2.3 µm unintentionally doped GaN buffer layer, and 18 nm thick *n*-type $Al_{0.25}Ga_{0.75}N$ layer. The epitaxial layers were deposited by metal organic chemical vapor deposition (MOCVD) growth technique on GaN buffers deposited on sapphire substrates. Device fabrication includes ohmic contacts formation after device isolation. Drain and source ohmic contacts with metal stack of Ti/Al/Ni/Au were obtained using e-beam metallization technique and then annealed in a nitrogen atmosphere. Ni-based Schottky contact was used as a gate finger. Ion implantation and dry etch processes were used for the device isolation. Devices were interconnected using Au interconnects. Transmission line measurement (TLM) and meander structures were used to study the sheet resistance, contact resistance, and isolation resistance. Output characteristics were measured on a 250 µm devices having an L_{SD} = 50.0 µm, explicitly used for the sensing applications. The 2DEG carrier mobility is 1300 cm^2/V s and sheet carrier density is 10^{13} cm^{-2}. Hall measured sheet resistance value is 550 Ω/square.

Fig. 1 demonstrates the schematic cross-section of the fabricated HEMT devices on (a) ion-implanted (b) mesa-isolated samples. All the samples used for comparison were from the same epi growth technique.

At first, different samples were implanted with multi-energy and multi-dose to produce an effective damage depth. Parameters used for ion implantation (I.I) are listed in Table 1. To make a highly resistive isolation region, devices were undergone to $^{40}Ar^+/^{14}N^+$ ion implantation including three and four energies (3 E & 4 E) of (20/35/65 keV & 20/35/65/ 160 keV), and doses of (4.2 × 10^{12}/6.3 × 10^{12} /1.11 × 10^{13} cm^{-2} & 4.2 × 10^{12}/6.3 × 10^{12} /1.11 × 10^{13}/ 1.11 × 10^{13} cm^{-2}) respectively. These energies produced an effective damage depth of 255 nm. The transport of ions in matter (TRIM) software was employed to compute ion ranges in GaN HEMT structures [26]. Fig. 2(a) and (b) represents the depth profiles of ion ranges for Ar^+ and N^+ implantation using ion energies 20 keV, 35 keV, 65 keV and 160 keV respectively. Fig. 2(c) shows the displacement profiles in AlGaN/GaN by $^{14}N^+$ and $^{40}Ar^+$ ions for successive 3 E and 4 E calculated using TRIM code. It was evident that heavier ion mass ($^{40}Ar^+$) have large collision cross sections and provided displacements at the shallower location with a higher concentration. Isolation using 4 E gives larger target depth in comparison to 3 E.

Secondly, Reactive ion etching (RIE) method was used as a dry etch technique employing single step and dual step etch processes. For optimization, different ratio combination of the flow rate of reacting gases (BCl_3/Cl_2/Ar), RF power and pressure were varied and investigated the impact of different mesa recipe/condition on the electrical performance of AlGaN/GaN HEMTs. The conventional single step BCl_3: Cl_2 based plasma chemistry (Recipe 1) with a specific combination of gas flow (3:1), RF power 75 W and pressure of 5 Pa was used for the mesa etching. Recipe 2 was generated by directly adding argon (Ar) in the single step Recipe 1. Next, the Double Step Recipe (Recipe 3) was created in which the samples were pre-treated in BCl_3: Ar (2:1) plasma in the first step at 100 W and pressure of 1 Pa. In the second step, the sample was etched using BCl_3: Cl_2: Ar (3:1:1) plasma chemistry. Recipe 4 was generated by reducing the power in Recipe 3. Table 2 gives the typical value of different experimental conditions, the ratio of flow rates of reacting gases, chamber pressure, and RF powers.

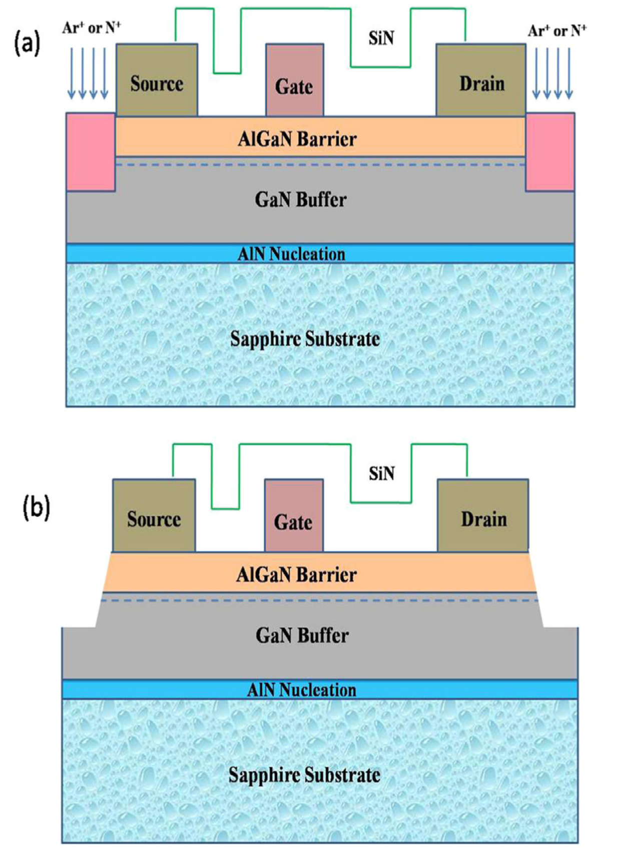

Fig. 1. Schematic cross-section of AlGaN/GaN HEMTs fabricated on (a) ion implanted and (b) mesa-isolated samples.

Table 1
Parameters used for multiple-energy and multi-dose ion implant.

Recipe	Ion energy (keV) and doses ($/cm^2$)				Source gas
3 Energy	20 4.2 × 10^{12}	35 6.3 × 10^{12}	65 1.11 × 10^{13}		Ar^+/N^+
4 Energy	20 4.2 × 10^{12}	35 6.3 × 10^{12}	65 1.11 × 10^{13}	160 1.11 × 10^{13}	Ar^+/N^+

3. Results and discussion

3.1. Isolation using ion implantation technique

This letter reports on the use of multiple incident ion energies and multiple ion doses to ensure highly resistive isolated region in AlGaN and GaN buffer. For comparison, three energy and four energy Ar^+ ions with ion energies (20/35/65 keV & 20/35/65/160 keV), and doses of (4.2 × 10^{12}/6.3 × 10^{12} /1.11 × 10^{13} cm^{-2} & 4.2 × 10^{12}/6.3 × 10^{12} /1.11 × 10^{13}/ 1.11 × 10^{13} cm^{-2}) respectively were used for implant-isolation.

To examine electrical parameters associated with isolated regions, we analyzed I–V characteristics of TLM structures. Isolation resistance was measured by meander structures. The recorded magnitudes of isolation resistance, specific contact resistance and sheet resistance after ion implantation are listed in Table 3. The reference sample (not implanted) showed a resistance value of (∼ 200 Ω). After implantation, the isolation resistance increased for both the energies (3 E and 4 E). In these AlGaN/GaN devices, use of 3 E and 4 E resulted in a slight change