Highly selective and low damage atomic layer etching of InP/InAlAs heterostructures for high electron mobility transistor fabrication

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Highly selective, low damage atomic layer etching (ALET) technology was developed for dry gate recess during the fabrication of InGaAs/InP/InAlAs high electron mobility transistors lattice matched to InP substrates. Etching characteristics of InP layer on top of InAlAs layer and the surface chemistry of the exposed InAlAs layer were investigated by utilizing angular resolved x-ray photoelectron spectroscopy. Finally, InAlAs Schottky diodes were fabricated by utilizing chlorine-based ALET technology and conventional Ar-based dry recess and their electrical characteristics were compared. By using the ALET, the etch selectivity as high as 70:1 was achieved for InP over InAlAs heterostructures and the stoichiometric modification of InAlAs was observed to be negligible after the recess etch process. Schottky diodes fabricated after the ALET exhibited the lower ideality factor and the higher Schottky barrier height compared to those fabricated with Ar-based plasma etching. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2754636]

InP-based high electron mobility transistors (HEMTs) have demonstrated ultrahigh speed characteristics with unity current gain cutoff frequency as high as 562 GHz and low noise characteristics and they are employed in analog integrated circuits for millimeter wave and optical fiber communications.[1,2] In the fabrication of InP-based HEMTs, gate recess is one of the most important processing steps, which determines the uniformity of the devices in terms of threshold voltages, transconductance, gate capacitances, and dispersion characteristics. Recently, Suemitsus *et al.* reported the two-step recess technology to improve device performance. A selective wet etching was utilized to remove the highly doped capping layers consisting of n^+-InGaAs and n^+-InAlAs, and the following Ar-based plasma etching was utilized to remove the InP etch stop layer under the gate opening prepared by electron-beam lithography.[3,4] However, Ar-based plasma etching technology utilizing energetic ions to achieve vertical etch profiles[5] tends to have low etch selectivity between InP and InAlAs (lower than 17) (Ref. 4) and may induce physical damage on the exposed surface of the InAlAs Schottky layer through the creation of surface defect including structural disruption, the formation of intermixing layer or stoichiometric modification, and the increment of surface roughness, resulting in a degradation of the gate diode characteristics.

In this letter, we have developed atomic layer etching (ALET) to overcome the potential problems that may occur during the conventional Ar-based plasma etching for the gate recess process. ALET has been investigated from the early 1990s for III-V compounds and silicon devices.[6,7] According to the previous study on ALET (Ne neutral beam ALET) of InP, the (100) InP etch rate remained as 1.47 Å/cycle that corresponds to 1 ML/cycle when the Cl_2 pressure and Ne neutral beam irradiation dose were higher than the critical values.[8] The surface roughness and the surface stoichiometry after ALET remained similar to those of InP before the etching. Etch selectivity of InP over InAlAs and the effect of ALET on the exposed InAlAs layer should be studied to employ ALET in the fabrication of InP-based HEMTs. To prove the viability of ALET, comparative studies were carried out for ALET and conventional Ar-based plasma etching in terms of the changes of surface stoichiometry and Schottky diode characteristics as a function of etching method have been investigated.

The ALET process steps performed in this study for the etching of InP are consisted of four sequential steps: (i) supply of Cl_2 gas for 20 s to the etch chamber so that chlorine can be adsorbed on the surface of InP (adsorption step), (ii) evacuation, (iii) Ne neutral beam irradiation to the Cl_2 adsorbed surface for the desorption of InP chlorides (desorption step), and (iv) evacuation of the InP chlorides.

Low energy Ne neutral beam was generated by a low-angle forward reflected neutral (LAFRN) beam technique. A LAFRN beam source was composed of a 13.56 MHz radio frequency (rf) ion source and a low angle planar reflector, and a three-grid inductively coupled plasma type ion gun was used as the ion source. In order to control the energy of Ne neutral beam, the voltage applied to the first grid located close to the source (accelerator grid) was fixed at 5 V and the voltage applied to the second grid (extractor grid) to control the beam flux was fixed at −250 V while the third grid was grounded. Ion energy and flux of Ne^+ ion beam measured by a Faraday cup before neutralizing were 27 eV and 1.2×10^{14} ions/cm^2 s, respectively. The neutralization efficiency of the neutral beam source is estimated to be higher than 99%. More details of the LAFRN beam source are described elsewhere.[9]

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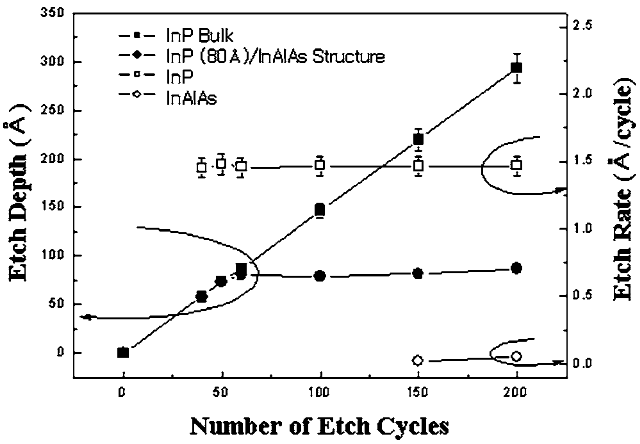

FIG. 1. Etch rate (Å/cycle) and etch depth of bulk InP and InP (80 Å)/InAlAs as a function of etch cycle for a monolayer etching condition. The Cl_2 pressure and Ne neutral beam irradiation dose were kept at 0.4 mTorr and 7.2×10^{15} at./cm^2 cycle, respectively.

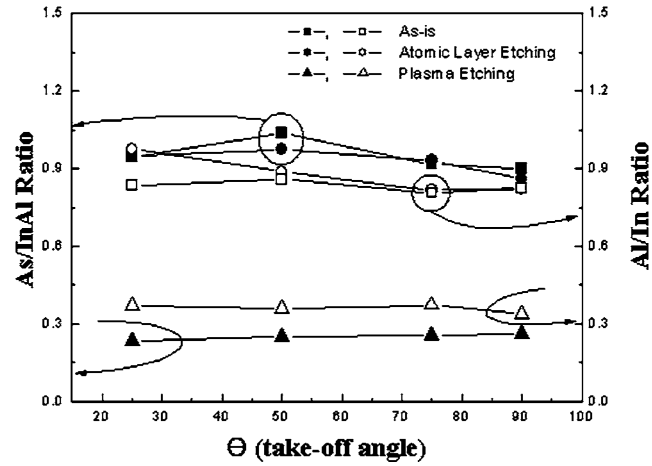

FIG. 2. Ratios of As/InAl and Al/In of InAlAs surface measured using angle resolved x-ray photoelectron spectroscopy before and after ALET and plasma etching. The etching condition for the ALET: Ne neutral beam irradiation dose (7.2×10^{15} at./cm^2 cycle), Cl_2 pressure (0.4 mTorr), and etch cycles (18 cycles). Plasma etching condition: the rf power (7 W), the bias voltage (−65 V), the gas chemistry [Ar (50 SCCM) at 20 mTorr], and the etching time (6 min).

The samples used in this experiment were bulk InP, $In_{0.52}Al_{0.48}As$ (3000 Å)/*n*-type InP, and InP (80 Å)/$In_{0.52}Al_{0.48}As$ (3000 Å)/*n*-type InP. Photoresist was used for the etch mask. Prior to loading into the chamber, the samples were dipped in a diluted HCl solution to remove the remaining native oxide on the surface followed by rinsing with de-ionized water and blow drying in N_2. The etched step height was measured using a step profilometer (Tencor Instrument, Alpha Step 500). An angular resolved x-ray photoelectron spectroscopy (ARXPS) (Thermo VG, MultiLab 2000, Mg $K\alpha$ source) was utilized to analyze the stoichiometric modification of InAlAs surface as a function of etching method. A semiconductor parameter analyzer (HP 4155B) was also utilized to analyze the dc current-voltage (*I-V*) of vertical Schottky diodes in dark environment.

Figure 1 shows the etch depth per cycle measured for bulk (100) InP and $In_{0.52}Al_{0.48}As$ using chlorine ALET. Also, the total etch depth of (100) InP and 80-Å-thick InP grown on the $In_{0.52}Al_{0.48}As$ are shown as a function of etch cycles. The $In_{0.52}Al_{0.48}As$ was grown on *n*-type InP substrate with the thickness of 3000 Å. As the etching condition, Cl_2 pressure during the adsorption step was maintained at 0.4 mTorr and ~27 eV Ne neutral beam irradiation dose during the desorption step was maintained at 7.2×10^{15} at./cm^2 cycle, which is the condition of 1.47 Å/cycle for InP corresponding to 1 ML etching of (100) InP per cycle.[8] As shown in the figure, at this etch condition, InP etch depth was increased linearly with increasing etch cycles and the etch depth/cycle of (100) InP was maintained at 1.47 Å/cycle regardless of number of etch cycles. However, when InP (80 Å)/InAlAs was etched, the total etch depth was increased linearly with increasing the number of etch cycles, and the calculated etch depth/cycle was maintained at 1.47 Å/cycle when the number of etch cycle was smaller than 60 cycles but, when the number of etch cycle was larger than 60 cycles, the etch depth was almost saturated and no noticeable etching was processed with increasing number of etch cycles. The etch depth/cycle for InAlAs was estimated to be less than 0.02 Å/cycle; therefore, during the etching of InP (80 Å)/InAlAs, the etch selectivity was higher than 70. The negligible etch rate of InAlAs obtained with the InP ALET condition appears not related to the differences in the binding energies of the components because the binding energy of In–P (2.054 eV) is similar to the binding energies between components in InAlAs [that is, In–As (2.087 eV) and Al–As (2.107 eV)].[10] Instead, it is possibly related to the formation of Al_xO_y on the exposed InAlAs after the removal of 80 Å InP during the ALET. When InAlAs is exposed, Al_xO_y can be formed on InAlAs by the residual oxygen originated from quartz erosion in the chamber and, due to the extremely low vapor pressure of Al_xO_y, the InAlAs is not easily removed by 27 eV Ne neutral beam during the ALET, which results in the extremely low etch rate of InAlAs at the InP monolayer etching condition.

Figure 2 shows the ratios of As/InAl and Al/In on the surface of InAlAs after the etching by the ALET measured using ARXPS. As references, the surface composition ratios of InAlAs before the ALET (as is) and after a plasma etching were included. For the ALET, 30% overetching of InP (80 Å) during the etching of InP (80 Å)/InAlAs was used for the etching condition of InAlAs, which corresponds to 18 cycles with the InP monolayer etching condition (0.4 mTorr of Cl_2 pressure and 7.2×10^{15} at./cm^2 cycle of Ne neutral beam irradiation dose). In the case of the plasma etching of InAlAs, a commercial etcher (Oxford, Plasmalab 80) was used and the operating conditions were 7 W of rf power, −65 V of bias voltage, 50 SCCM (SCCM denotes cubic centime per minute STP) Ar, and 20 mTorr of operating pressure, which is a low damage etch condition of InP. With this plasma etching condition, the InP etch rate was 4 Å/min, and therefore 6 min of etching time was used for the etching of InAlAs as 30% overetch condition of InP (80) during the etching of InP (80 Å)/InAlAs. When we compare the surface composition of InAlAs after the etching by ALET to that by a plasma etching, "apples to apples" comparison of a plasma etching to ALET by using a similar bombardment energy and reactive gas was not possible because the operating regimes of the equipments were completely different. Instead, optimum etch conditions that can be achieved with each etch methods were compared, as shown in Fig. 2. As shown in the figure, the ratios of As/InAl for as is, after the ALET, and after the plasma etching were in the range of 0.9–1.04, 0.86–0.97, and 0.23–0.26, respectively. No signifi-

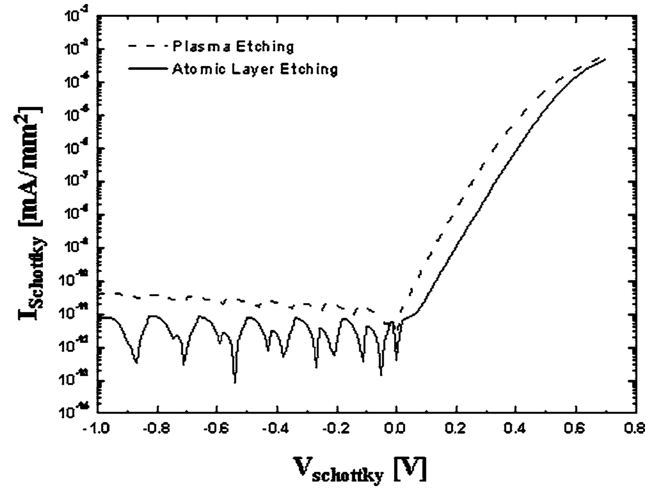

FIG. 3. dc *I-V* characteristics of the Schottky diodes fabricated after the ALET and plasma etching. The etching condition for the ALET: Ne neutral beam irradiation dose (7.2×10^{15} at./cm^2 cycle), Cl_2 pressure (0.4 mTorr) and etch cycles (62 cycles) (currently, 1 cycle time is 82 s due to low neutral beam flux). Plasma etching conditions: the rf power (7 W), the bias voltage (−65 V), the gas chemistry [Ar (50 SCCM) at 20 mTorr], and the etching time (20 min).

cant change of ratios was observed as a function of take-off angle. Also, the ratios of Al/In for as is, after the ALET, and after the plasma etching were in the range of 0.80–0.86, 0.81–0.97, and 0.33–0.37, respectively. Therefore, no significant change of the surface composition was observed after the ALET while significant decrease in the ratios of Al/In ratio and As/InAl was observed after the plasma etching. The decrease in the ratios of Al/In and As/InAl after the plasma etching is believed to be related to the differences in the sputter yield of each component of InAlAs. During the sputtering by Ar ions in the plasma, due to the differences in the energy transfer coefficients $4mM/(m+M)^2$ (where m is the mass of the target atom and M is the mass of the sputter ion), the sputter yield will be higher in the sequence of Al, As, and In because the energy transfer coefficient is lower in the sequence of Al, As, and In. On the other hand, no significant change in the surface composition after the ALET appears to be related to the formation of aluminum oxide on the InAlAs surface as mentioned above and the prevention of Cl_2 adsorption on the InAlAs surface, which results in no significant removal of InAlAs during the desorption step at the low Ne energy. The surface modification, which is physical damage, caused by the plasma etching during the gate recess process of InP-based HEMTs is one of the serious problems in the HEMT fabrication and the use of ALET of InP/InAlAs for the gate recess process can be a choice of the gate recess etching method.

To investigate the effect of etching methods on the electrical characteristics of the devices, vertical Schottky diodes were fabricated by using heterostructures of InP (80 Å)/$In_{0.52}Al_{0.48}As$ (3000 Å)/n-InP substrate. Schottky contact was formed on top of $In_{0.52}Al_{0.48}As$ (3000 Å) layer by the e-beam evaporation of Ti (200 Å)/Pt (200 Å)/Au (2000 Å) after the etching of InP (80 Å) by the ALET (62 cycles) and the Ar-based plasma etching (20 min) with the conditions presented in Fig. 2. Back side Ohmic contact was formed by the e-beam evaporation of Ni (100 Å)/Ge (450 Å)/Au (1500 Å), followed by a rapid thermal annealing at 275 °C for 45 s under N_2 ambient prior to the front side InP etching for Schottky diodes. The dc *I-V* characteristics of the Schottky diodes fabricated after the ALET and plasma etching are shown in Fig. 3. The Schottky diodes fabricated with the ALET exhibited better electrical characteristics than the diode fabricated after the plasma etching in terms of leakage current, Schottky barrier height (Φ_B), and ideality factor (η). Table I shows the values of Schottky barrier height (Φ_B) and Schottky diode ideality factor (η) measured using a standard *I-V* technique. The higher Schottky barrier height (Φ_B) and lower ideality factor (η) obtained by using the ALET are believed to be due to the lower physical damage (surface stoichiometric modification) of InAlAs surface after the ALET.

TABLE I. Summary of the parameters of Schottky diodes fabricated after ALET and plasma etching.

	Ideality factor (η)	Schottky barrier height (Φ_B)
Plasma etching	1.25	0.56 eV
Atomic layer etching	1.17	0.64 eV

In this study, chlorine-based ALET was used in the etching of InP (80 Å) on $In_{0.52}Al_{0.48}As$ (3000 Å)/n-InP substrate as a possible damageless etching method in the gate recess process of InP-based HEMT device, and the etched surface characteristics and Schottky diode characteristics fabricated after the etching by the ALET were compared with those by a conventional plasma etching. The etching of InP by the ALET with a condition for 1 ML etching of InP, which corresponds to 1.47 Å/cycle, showed the etch selectivity of InP over InAlAs higher than 70, and by the ALET, surface modification which is commonly observed for plasma etching could be dramatically reduced to a level similar to as is. The characteristics of Schottky diode fabricated after the etching by the ALET also showed higher Schottky barrier height and lower ideality factor compared to the device fabricated after the etching by a plasma etching.

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