Effects of Electrochemical Etching on InP HEMT Fabrication

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Abstract

Optimum device performance in terms of noise and gain of AlInAs/GaInAs/InP High Electron Mobility Transistors (HEMTs) requires minimizing the contact resistance R_C. In several HEMT device manufacturing steps it is common to expose highly-doped semiconductors layers to heated solvents for prolonged periods of time. It is shown here that even a small amount of water or water vapor present during photoresist removal, metal lift-off or related processes can dramatically affect the final device performance by promoting electrochemical etching of the semiconductor layers adjacent to metal stacks. In this paper, the impact of metal lift-off on erosion of HEMT epitaxial layers and Ohmic contact resistance is studied.

INTRODUCTION

InP-based HEMTs are crucial components for manufacturing low-noise amplifiers in the semiconductor industry today, offering high-speed, high-gain and low-noise both at room and cryogenic temperatures. To achieve the ultimate performance of a HEMT, the reduction of the contact resistance plays a central role [1].

Electrochemical etching of the top GaAs layer adjacent to the Ohmic stack layer has already been observed in the fabrication of GaAs-based semiconductor devices due to the use of N-Methyl-2-Pyrrolidone (NMP) or other solvents [2-4] heated up to temperatures of 90-120°C to remove hard-baked resist films. While galvanic etching was effectively used to fabricate deep profiles of gate grooves during wet-chemical recess of AlInAs/GaInAs/InP HEMTs [5], to our knowledge, impact of metal lift-off and resist removal on layer erosion for InP-based devices was never reported. In this paper, we present the effect of electrochemical etching during Ohmic metal lift-off using NMP on highly doped GaInAs/AlInAs composite cap layer, and consequently Ohmic contact resistance degradation.

It was shown that anodic oxidation of the semiconductor takes place when water is present during photoresist removal or metal lift-off steps [4]. Exposed metal is believed to enhance the semiconductor oxidation, and the resulting oxide is subsequently dissolved in the surrounding solution resulting in epitaxial layer erosion near the metal/semiconductor interface. Consequently, the metal/semiconductor junction resistance increases above its minimum and presents non-optimal values. The extent of electrochemical etching is increased when exposure time is lengthened to ensure a complete and clean wet process. Furthermore, increasing the doping of the semiconductor layers to further reduce the contact resistances can enhance the layer corrosion due to more electrons being available for electrochemical oxidation.

Avoiding water or water vapor contamination during semiconductor fabrication steps poses a challenge since solvents beakers heated to high temperatures are usually held in water baths in order to control the solvent temperature more accurately. During insertion of samples into solvents, water vapor from the bath or water molecules from air can unintentionally get into the beaker, or coat samples, thereby allowing the electrochemical etching of semiconductor to take place.

Fabrication of low-noise InP HEMTs for cryogenic applications requires a very precisely executed and optimized process flow because device properties are very susceptible to any surface treatments such as oxidation, de-oxidation or desired/undesired layer etching. To preserve the optimum device performance, high device yield and process repeatability, special attention needs to be paid to characterization and control of galvanic etching during device processing.

FABRICATION

All experiments were carried out on the epitaxial layer stack presented in Fig. 1 [6]. Transfer length method (TLM) structures were fabricated by optical lithography, following all the same process step sequences and procedures as for a full HEMT device. Device fabrication began with the formation of the source and drain Ohmic contacts by optical lithography, evaporation of Ge/Au/Ni/Au metal stack after the removal of the native oxide by low-energy Ar sputtering, and rapid thermal annealing. Next, device isolation was performed using a citric acid solution for the GaInAs/AlInAs cap layers, where the InP etch stop was removed with an HCl-based diluted solution.

EXPERIMENTS

Exact fabrication steps were followed for all the samples except for the Ohmic lift-off procedure. The first process split consisted of using pure NMP inside a 100 ml beaker, while 1 ml and 3 ml H_2O were added for the second and the third split respectively. It should be noted that special attention was devoted to avoiding any kind of water or water vapor contamination for the first split.

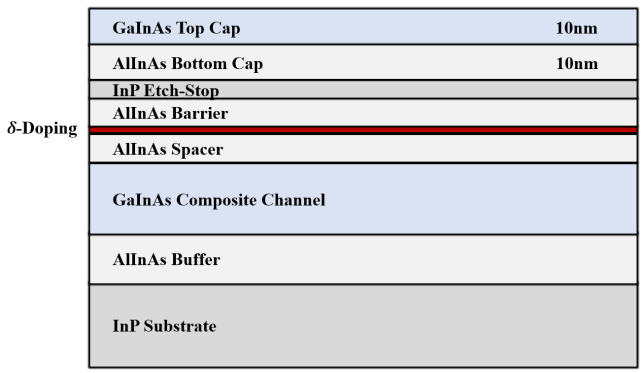

Fig. 1. Schematic cross-section of the epitaxial layer structure used in the experiment.

Following the fabrication of the TLM structures, with spacings ranging from 2 µm to 10 µm, their resistance was measured via the 4-point resistivity measurement at room temperature, and contact and sheet resistance were extracted for each split. Fig. 2 shows the extracted contact resistance R_C value versus lift-off time and H_2O concentration. The graph shows that an inclusion of 3 ml water can cause significant increase of the R_C, which is even more pronounced if the duration of the process is extended. TLMs with 1 ml of H_2O also show higher contact resistance compared to pure NMP. We show below that increased R_C is due to an undercut etching of the GaInAs cap underneath the metal contact.

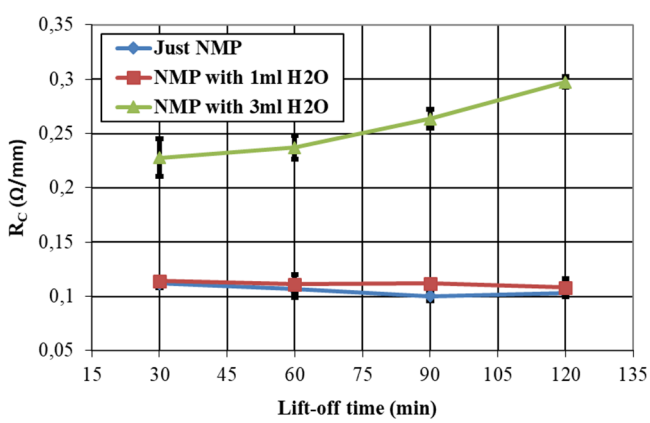

Fig. 2. Extracted contact resistance of fabricated TLM structures. SEM-verified spacings were used for extraction.

Scanning Electron Microscopy (SEM) images were obtained after lift-off and annealing to confirm the layer erosion below the Ohmic metal layer stack. As a consequence of electrochemical etching of the layers, the contact edges (periphery) remain un-annealed due to the missing cap material underneath. Fig. 3 shows the top view of the deposited contact, where resist lift-off was performed using NMP and 3 ml of water, with the non-annealed part depicted with arrows. Lateral etching depth is increasing with the length of the exposure to the mixture of solvent and H_2O effectively widening the distance between two contacts and increasing the contact resistance as presented in Fig. 2.

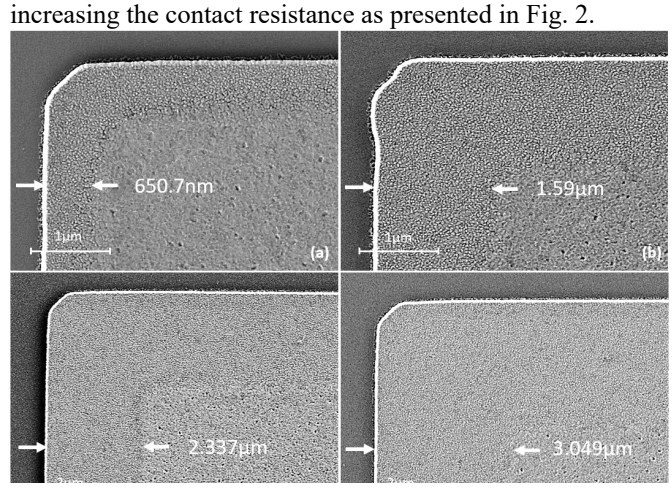

Fig. 3. SEM images the of the Ohmic contact pad with different exposure times to NMP and 3 ml H_2O: 30 min (a), 60 min (b), 90 min (c) and 120 min (d). Lateral etching encroachment is depicted with arrows.

The cross-sectional SEM image of the deposited contact with the cap material visibly etched underneath the metal is shown in Fig. 4.

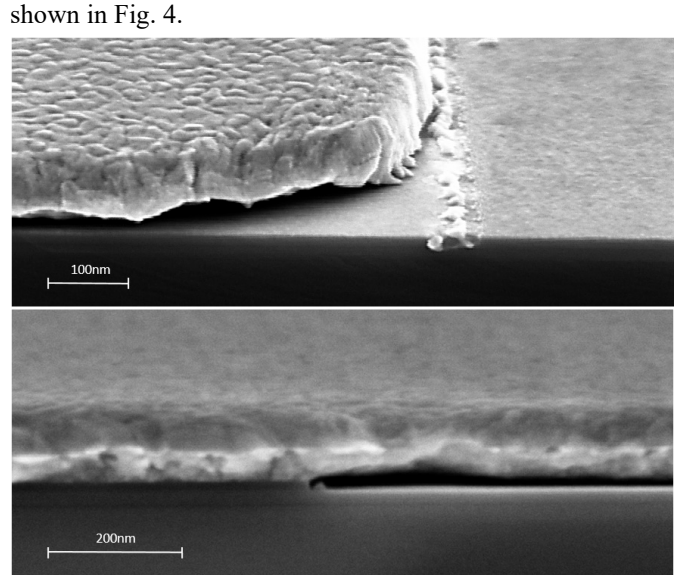

Fig. 4. Cross-sectional SEM images of the deposited contact showing galvanic etching of the cap layer.

SEM images of TLM structures using pure NMP or 1 ml of water in NMP for metal lift-off also show presence of galvanic etching, although in lesser extent than shown in Fig. 3. Therefore the R_C values obtained in Fig. 2 in all three cases are not optimal. To obtain the minimum R_C and avoid layer corrosion, less aggressive Dimethyl Sulfoxide (DMSO) can be used as a substitute for NMP. However, using a weaker solvent presents a risk for surface contamination with resist residues.

To confirm the dependence of the doping level of the cap on the erosion rate of the metal, an additional experiment was performed using an identical epitaxial layer structure with 50% lower cap doping. Following an equivalent sequence of steps as detailed previously, both the sample with higher and the sample with lower doping were exposed to NMP with 3 ml H_2O during 2 h. Fig. 5 shows the width increase of the non-annealed contact region for the structure with the higher doped cap. As assumed, the metal corrosion is aggravated with increased doping of the semiconductor since the electrochemical oxidation is enhanced due to the presence of more electrons. Consequently, the desired contact resistance decrease obtained by utilizing a highly doped cap is countered and even exceeded by its increase due to layer erosion. Therefore, using highly doped cap layers as a common approach to reduce contact resistance can have opposite outcome – higher resistance values compared to the structures with lower doping and less sensitive to electrochemical etching.

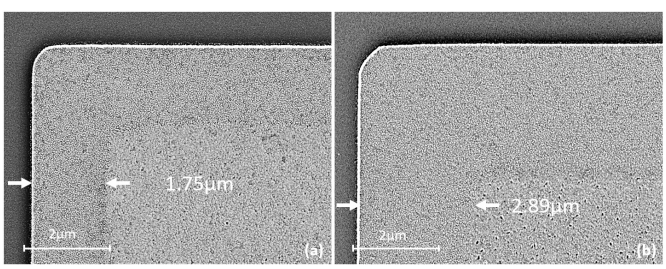

Fig. 5. SEM images the of the Ohmic contact pad of epitaxial layer structures with low (a) and highly doped cap (b) exposed to NMP and 3 ml H_2O for 120 min. Lateral etching encroachment is depicted with arrows.

DISCUSSION

When NMP is mixed with a small amount of water, NMP molecules hydrolyze to yield γ-methylaminobutyric acid [7] and generate additional reactive H^+ ions in the solvent. The solvent thus becomes corrosive to the GaInAs surface. To show the mechanism accounting for undercut etching of GaInAs at metal/semiconductor junction, the acidic hydrolysis of NMP was investigated by measuring the H^+ ion concentration in NMP with different content of added water. The relative concentration of H^+ was measured using a pH meter in NMP with 1, 3, 8, 13 vol% of H_2O, heated to 90°C, for 2 hours. It is shown in Fig. 6 that more H^+ are generated when more water is added to NMP. In the case of our study, the GaInAs at metal/semiconductor junction is very reactive to small amount of H^+ in the lift-off solvent because it is highly doped. The inert Au from the Ohmic metal layer stack acts as an anode leading to local electrochemical reaction together with electrons from the highly-doped GaInAs and H^+ ions.

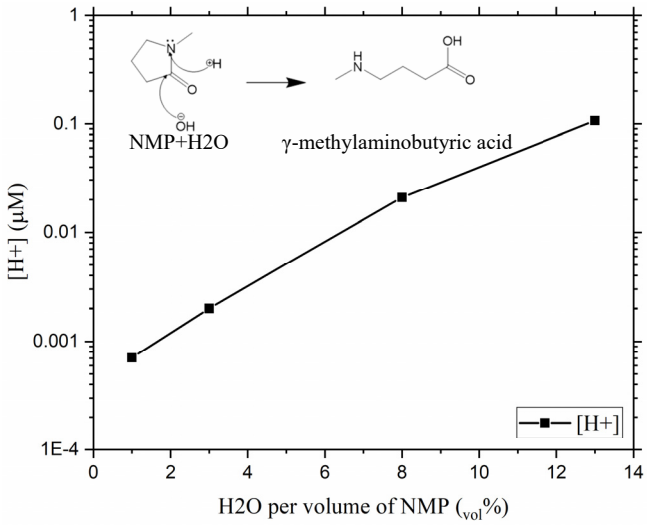

Fig. 6. Measured H^+ concentration in NMP for different amounts of dissolved H_2O.

CONCLUSIONS

We have investigated the occurrence of galvanic etching of GaInAs/AlInAs and its effects on the R_C of InP HEMTs. The results indicate that the presence of H_2O or H_2O vapor can catalyze etching of the semiconductor by the solvent such as NMP during resist removal and lift-off with the extent of reaction increasing with time. SEM images revealed that even without intentionally adding water, layer corrosion in some amount happens when using NMP as a solvent for lift-off. Although just 1 ml of H_2O does not significantly affect the R_C with respect to the value obtained with pure NMP, the presence of 3 ml can largely increase the contact resistance and result in severe device performance degradation.

The erosion rate of the metal is influenced by the doping concentration in the semiconductor, being more sensitive and leading to higher contact resistance values when the doping level of the cap is increased.

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ACRONYMS

HEMT: High Electron Mobility Transistor
NMP: N-Methyl-2-Pyrrolidone
TLM: Transfer Length Method
DMSO: Dimethyl Sulfoxide
SEM: Scanning Electron Microscopy