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Ultra-low rate dry etching conditions for fabricating normally-off field effect transistors on AlGaN/GaN heterostructures

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ABSTRACT

Enhancement-mode transistors with uniform turn-on threshold voltage (V_{th}) can be achieved using low damage and low rate gate recess etching techniques. In this work, dry etching conditions for a AlGaN/GaN heterostructure with an ultra-low etching rate of 1.5 nm/min were demonstrated and we succeeded the possibility to achieve a low etch rate of an AlGaN/GaN heterostructure in a Cl_2/BCl_3 plasma using inductively coupled plasma (ICP). The etching development was successfully implemented in the achievement of a normally-off GaN/AlGaN based transistor. The optimal recess depth was determined after fabrication of various devices with different recess depth values and with various dry etching conditions and after examining the performances of fabricated devices various conditions, and determining the dependence of recess time. The optimized etching condition resulted in low damage and smooth morphology of the etched AlGaN/GaN surfaces. Fine control of the depth of the gate region recess was achieved for the AlGaN/GaN heterostructure without any etch-stop layer, and validated for the fabrication of field effect transistors (FETs) using conventional processes. The fabricated normally-off Al_2O_3/AlGaN/GaN MOSFETs delivered a high positive V_{th} of $+5.64$ V with a low off-state leakage current of $\sim 10^{-7}$ A/mm and lower current collapse.

1. Introduction

Wide band gap semiconductors such as GaN, AlN, SiC, and diamond are expected to play an important role in next-generation electronic devices [1–4], in large part because these wide band gap semiconductors have ability to withstand both harsh environments and high temperature. In particular, the AlGaN/GaN heterostructure field effect transistor (HFET) which has a high carrier concentration two-dimensional electron gas (2DEG), exhibits not only excellent breakdown characteristics, but also low on-resistance and high switching speed. For these reason, AlGaN/GaN devices are promising for many applications, for example, in such fields as the military, aerospace, automotive and petroleum industries, engine monitoring, as well as flame and solar UV detection [5,6], AlGaN/GaN heterostructure field-effect transistors have been intensively investigated for a number of high temperature, high power and high frequency electronic device applications [7,8]. Because of their high critical breakdown fields, high saturation velocities, and high thermal conductivities, GaN-based high electron mobility transistors (HEMTs) have been specifically targeted as high power, high frequency, and high temperature electronic devices for mobile communication systems, radars, and power electronics [9]. At the same time, many achievements have been reported in the development of nitride device fabrication process [10–20].

In the fabrication of normally-off AlGaN/GaN HFET devices, removal of the shallower 2DEG, as well as fine control of the etching depth, excellent uniformity and smooth surface morphology are very important to device performance. The recessed gate approach is one of the attractive candidate methods for fabricating normally-off HFETs. Achieving uniform turn-on threshold voltage (V_{th}) is also an important factor in normally-off HFET device fabrication. For this reason, one of most reliable technologies for normally-off device fabrication involves finely controlled etching under the gate region [8,9]. It is possible to removing the 2DEG under the gate region and produce a smooth surface and defined etching depth using ultra-low rate dry etching technology.

In this work, dry etching conditions for a AlGaN/GaN heterostructure with an ultra-low etching rate of 1.5 nm/min were demonstrated and we achieved the possibility to achieve a low etch rate of an AlGaN/GaN heterostructure in a Cl_2/BCl_3 plasma using inductively coupled plasma (ICP). The etching development was successfully implemented in the achievement of a normally-off GaN/AlGaN based transistor. The optimal recess depth was determined after fabrication of various devices with different recess depth values and with various dry etching conditions and after examining the performances of fabricated

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2. Experiments

To investigate ultra-low rate dry etching conditions in this work, sample wafers were grown on 2 in. sapphire substrates using the low pressure organometallic vapor phase epitaxy (OMVPE) method. The schematic structure of the AlGaN/GaN-on-sapphire substrate is shown in Fig. 1. First, a semi-insulating GaN layer was deposited 2.2-µm-thick on 2 in. c-plane (0001) sapphire substrates, and then a 25 nm thick AlGaN layer with 25% Al composition was grown up without any capsulation layer. The Hall mobility and sheet carrier concentration were measured at room temperature and were found to be 1010 $cm^2/(V{\cdot}s)$ and 1.19×10^{13} cm^{-2}, respectively. The dry etching process for the AlGaN/GaN heterostructure was performed using inductively coupled plasma (ICP) with a Cl_2/BCl_3 gas mixture plasma, after patterning with photoresist (PR) using a I-line stepper. The recessed etching depth was measured by atomic force microscopy (AFM) after removing the PR.

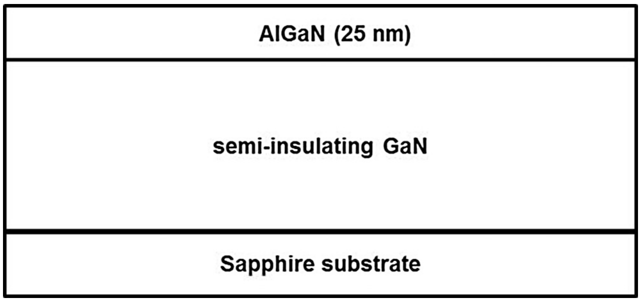

Fig. 1. Schematic structure of 2-in. scale AlGaN/GaN-on-sapphire.

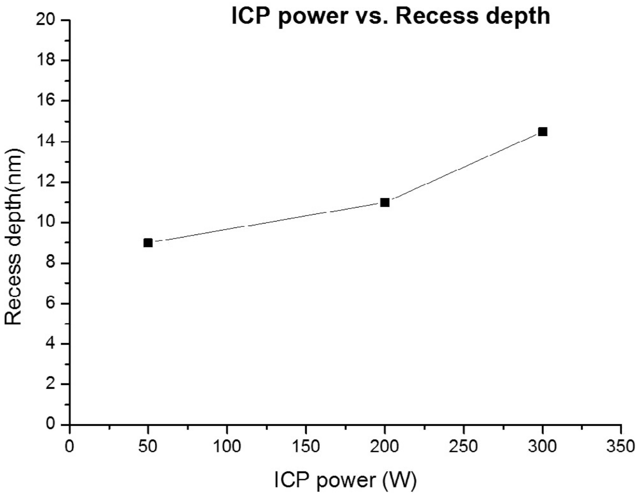

Fig. 2. Results of recessed depth with various ICP power for 120 s recess time under 5 mTorr chamber pressure.

In heterostructure fabrications, the etch rate is related to the ICP and bias power, gas mixture and chamber pressure. The relationship between the ICP power and recessed depth was studied here in this work. For this purpose, various ICP powers were applied to ach sample for the same process times and the same chamber pressure. The resulting recess depth was determined by AFM image analysis. Fig. 2 shows the results of this experiment with 120 s recess time under 5 mTorr chamber pressures. With an ICP power of 300 W, the recessed depth was 15 nm for 120 s recess time. With 200 W of ICP power, the recessed depth was 11 nm for 120 s recess time. Only 9 nm was recessed with an ICP power of 50 W for 120 s recess time. The dependence of the recess depth on ICP power was easy to observe. Based on these results, a reduction in ICP power was observed to decrease the recess depth under the AlGaN/GaN layer. Nonetheless, the calculated etch rate determined for each ICP power was not sufficient for application in the fabrication of a normally-off device. The slowest etch rate was still 0.08 nm/s, and controlling the defined etch depth with good accuracy and uniformity remained difficult. One possible alternative for reducing the etch rate without changing the gas mixture, here the flow rate of Cl_2 was 3 sccm, and that of BCl_3 was 16 sccm, is to change the pressure in the process chamber.

Kim et al. [21] reported, that the etch rate of AlGaN decreased with the increase of operational pressure but the etch rate of GaN shows a maximum etch rate at 30 mTorr. They reported the AlGaN etch rate of about 500 nm/min at 30 mTorr, which means about 10 nm/s. This rate is too fast to apply to our process of device fabrication with good control of recess depth.

To further investigate optimal ultra-low dry etching conditions in this work, the recess time for the patterned wafer at fixed ICP power was changed to 100 W and 50 W, and we also changed the chamber pressure, to 5 mTorr, 10 mTorr and 20 mTorr. Fig. 3 shows the results of the recessed depth according to recess time with various ICP power conditions. The green[1] points in Fig. 3 indicate the recess depths for 100 W ICP power, 3 W bias power and 5 mTorr chamber pressure, depending on recess time. The red points in Fig. 3 indicate the recess depths for 50 W ICP power, 3 W bias power and 5 mTorr chamber pressure, depending on recess time. The black points in Fig. 3 indicate the recess depths for 50 W ICP power, 3 W bias power and 10 mTorr chamber pressure, depending on recess time. At a chamber pressure of 20 mTorr, the processing plasma was unstable, and we could not perform the recess experiments at this chamber pressure.

We obtained stable plasma only at chamber pressures of 5 mTorr and 10 mTorr. The green and red points in Fig. 3 show that changing the ICP power did not reduce the etch rate remarkably. The calculated slope of the red points was 0.1 nm/s, which means an etch rate of 6 nm/min. In contrast to this result, the red and black points in Fig. 3 show that a change in chamber pressure reduces the etch rate more effectively. The calculated slope of the black points was 0.025 nm/s, which means an etch rate of 1.5 nm/min. To effectively reduce the etch rate, changing the process pressure in the reaction chamber may be a more dominant factor than changing the ICP power in the plasma etching process.

3. Results and discussion

Considering these results, the surface morphology of the recessed region was then investigated further. Fig. 4 shows the AFM image analysis of the surface morphology of the recessed region after each recess process, with corresponding recess conditions. Fig. 4(a) and (d) show a top view, (b) and (e) show a 3D view and (c) and (f) show the cross profile of the A-A′ recessed region for condition A and condition B,

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[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.