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TMAH-based wet surface pre-treatment for reduction of leakage current in AlGaN/GaN MIS-HEMTs

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ABSTRACT

The pre-passivation surface treatment process with tetramethylammonium hydroxide (TMAH)-based wet solution was proposed for the minimization of the leakage current (I_{leak}) in AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs). This process step contributes to the simultaneous decrease of the surface current (I_{surf}) in the active region of device and mesa-isolated region by removing the surface states and traps related to nitrogen (N) vacancy, Ga-oxide, and dangling bonds. Using the surface treatment, the fabricated device achieves a lower off-state current (I_{off}) of $\sim10^{-12}$ A/mm, a higher on/off current ratio (I_{on}/I_{off}) of $\sim10^{11}$, a small subthreshold swing (SS) of 68.4 mV/dec. The reduced I_{leak} also improves breakdown voltage (BV). In addition, the interface trap density (D_{it}) between the SiN layer and the AlGaN surface was extracted to evaluate the quality of the SiN/GaN interface, which showed that the treatment decreases the D_{it} with reduction of the surface defects.

1. Introduction

AlGaN/GaN-based metal-insulator-semiconductor high-electron mobility transistors (MIS-HEMTs) have been studied for high frequency and high power applications, owing to outstanding material properties of III-nitrides such as a high electron mobility, a high electron saturation velocity, and a high breakdown electric field [1–5].

However, the epitaxial AlGaN/GaN layers grown for the device fabrication suffer from the existence of many states and traps at surface as well as in buffer layer, related to dislocations, nitrogen (N) vacancy, or oxygen (O) incorporation. Especially, the trapping effects through the surface states leads to a high device leakage current (I_{leak}) which results in high off-state current (I_{off}), the poor subthreshold swing (SS), low breakdown voltage (BV), high noise, and low power efficiency [6–8]. To suppress the I_{leak}, the process step for the reduction of surface current (I_{surf}) is required. Several groups have reported a surface passivation with SiN layer for reduction of the I_{surf} and surface states [9,10]. However, since this method occasionally suffers from difficulty in obtaining a high interface quality between SiN and GaN layer [11], an appropriate surface treatment prior to SiN passivation is important in improving the interface quality [12]. Further, the I_{surf} also flows through the leakage pass created by surface states and traps, which are related to plasma etching for the device isolation [13,14], and this current can be significantly increased if the plasma damaged surface is not properly recovered by an appropriate treatment. Reduction of the leakage current due to plasma etching required for the device isolation is therefore very important especially for a high voltage application. Consequently, to minimize the I_{leak} of the device, it is essential to eliminate the origins for the I_{surf} in mesa-etched region as well as active region of the device. It is known that the wet etching based on tetramethylammonium hydroxide (TMAH) solution removes native Ga-oxide from the GaN surface because the Ga-oxide is dissolved in hydroxide solutions and the surface layer becomes N-terminated as hydroxide solutions such as KOH and NaOH do [15,16]. Since the OH^- ions in hydroxide solutions react with Ga atoms, the Ga-terminated surface with many N vacancy-related dangling bonds is converted into the N-terminated surface by removing the N vacancy [17]. It was also reported that the TMAH treatment on the plasma etched GaN surface effectively removes the plasma damage from the surface, but also smoothens the GaN surface [18–20].

In this work, the TMAH-based surface pre-treatment prior to SiN passivation was introduced, which simultaneously reduces the I_{surf} through both the active region and the mesa-isolated region. The effect of the treatment on the reduction of the I_{surf}

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was verified by measuring the I_{surf} according to the treatment time. The interface quality between the TMAH-treated GaN surface and the SiN gate dielectric layer was also evaluated by extracting the interface trap density (D_{it}).

2. Device fabrication

The AlGaN/GaN heterostructure was grown by metal–organic chemical vapor deposition (MOCVD) on *c*-plane sapphire substrates. The structure consisted of 2 μm-thick GaN buffer layer, 60 nm-thick undoped GaN channel layer, 22 nm-thick AlGaN layer, and 2 nm-thick GaN cap layer. Two-dimensional electron gas density (2DEG) of 9.7×10^{12} cm^{-2} and electron mobility of 1520 cm^2/V·s were estimated by Hall measurement at room temperature (RT), respectively. The schematic cross section of the fabricated MIS-HEMT is shown in Fig. 1(a). The gate length (L_G) and the gate-to-source distance (L_{GS}) are 2 and 5 μm, respectively. The gate-to-drain distance (L_{GD}) is designed to be 5, 10, and 20 μm. The fabrication process started with mesa etching using Cl_2/BCl_3 plasma-based inductively coupled plasma (ICP) for device isolation. Etching depth for device mesa isolation was about 250 nm. The wet surface treatment was then carried out using TMAH solution (5% concentration) at 90 °C for 3 min prior to SiN deposition. It is noticed that the TMAH treatment was applied to the surface of the device active region and the mesa-etched region for the isolation, as shown in Fig. 1(b) and (c), respectively. In the active region, the treatment removes the native Ga-oxide formed at the GaN surface as well as the N vacancy-related dangling bond to change the surface to the N-terminated surface. Same treatment effect can be also achieved at the mesa-etched surface. Furthermore, the TMAH also smooths the rough GaN surface due to the plasma etching to remove the plasma damage from the etched surface as discussed above. After the treatment, 20 nm-thick SiN layer as a gate dielectric layer was deposited using plasma-enhanced chemical vapor

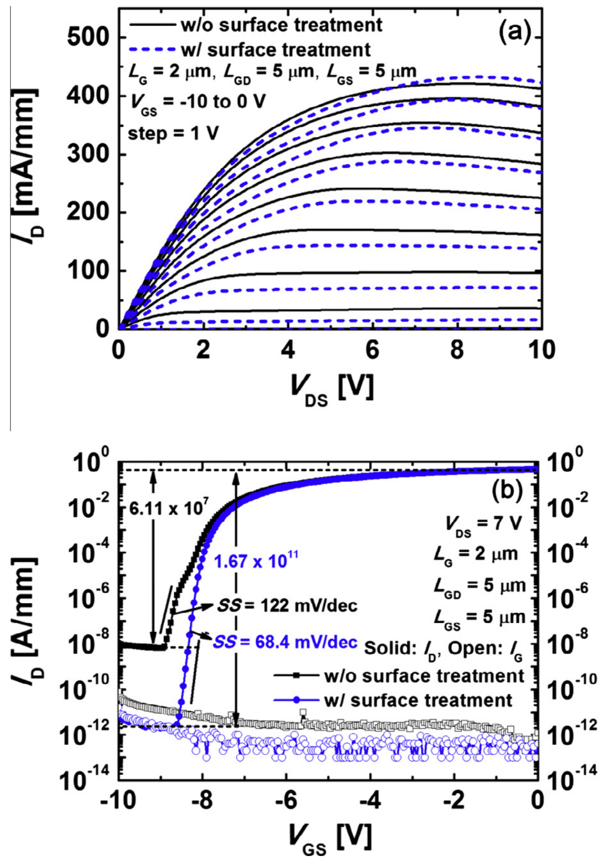

Fig. 2. (a) Output and (b) I_D and I_G characteristics at V_{DS} of 7 V of the fabricated MIS-HEMTs with and without the TMAH-based surface treatment.

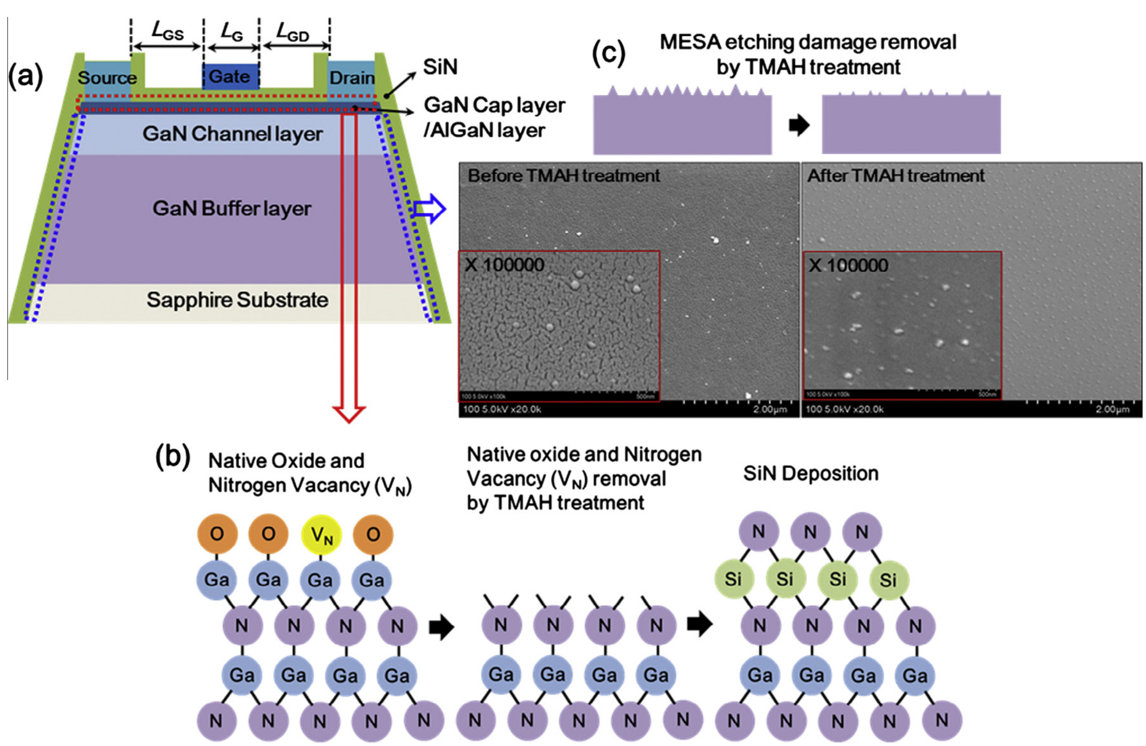

Fig. 1. (a) Schematic cross section of the AlGaN/GaN heterojunction-based MIS-HFET. (b) Schematic of the atomic arrangement at SiN/GaN interface and (c) SEM images of the etched surface without and with the TMAH-based surface treatment.