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La_2O_3 gate dielectrics for AlGaN/GaN HEMT

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ABSTRACT

The annealing temperature dependent electrical characteristics of La_2O_3 gate dielectrics for W gated AlGaN/GaN high electron mobility transistors (HEMTs) have been characterized. The threshold voltage (V_{th}) has been found to shift to positive direction with higher temperature annealing, exceeding those of Schottky HEMTs, presumably attributed to the presence of negative fixed charges at the interface between La_2O_3 and AlGaN layers. At a high temperature annealing over 500 °C, a high dielectric constant (k-value) of 27 has been achieved with poly-crystallization of the La_2O_3 film, which is useful to limit the reduction in gate capacitance. A high k-value for La_2O_3 gate dielectrics and the presence of negative charges at the interface are attractive for AlGaN/GaN HEMTs with low gate leakage and normally-off operation.

1. Introduction

AlGaN/GaN high electron mobility transistor (HEMT) structures have been strong candidates for power devices with low power consumption; low on-state resistance due to their high electron mobility of 2 dimensional electron gas (2DEG) of over 1000 cm^2/Vs with reduced drift region owing to large breakdown field of 3 MV/cm [1–3]. As the application of positive voltage to the Schottky gate is in the forward bias condition, the gate leakage current exponentially increases with gate voltage. Therefore, an overdrive voltage to increase the channel current is limited to gate leakage current [4]. A straightforward approach to suppress the gate leakage current and to allow larger overdrive is to adopt metal-oxide-semiconductor (MOS) structure, inserting gate dielectrics between the metal and AlGaN layer [5]. Various oxides, including SiO_2, Si_3N_4, Al_2O_3, Y_2O_3, Gd_2O_3 and HfO_2, and also polymers have been reported so far, and the interface properties have been characterized [5–10]. Some of the drawbacks of the MOS structure include the gate capacitance decrease due to series connection of gate dielectrics to AlGaN layer, which reduces the drain current as well as transconductance [5]. Also, due to increased gate-to-channel distance by gate dielectrics insertion, the V_{th} shifts to negative direction, which poses difficulty in designing driver circuits [5]. A thinner gate dielectric layer can suppress those side effects to some degree, however, the thickness is limited to the gate leakage current. Therefore, the use of a gate dielectric material with a high permittivity, a high k-value, is mandatory to satisfy both requirements. As for V_{th} shift, a negatively charged interface at the dielectric and the AlGaN layer is preferable as the charges shift the V_{th} to positive direction [11]. In this paper, La_2O_3 films with a bandgap and a k-value of 5.5 eV and over 20, respectively, have been used [12]. A systematic study on the influence of annealing temperature on electrical characteristics is conducted.

2. Device preparations

AlGaN/GaN HEMT with La_2O_3 gate dielectrics was fabricated on an undoped 24-nm-thick $Al_{0.3}Ga_{0.7}N$ layer on GaN layers epitaxially grown on a Si (111) substrate. After chemical cleaning of the samples with sulfuric acid and hydrogen peroxide mixture followed by dipping in diluted HF solutions, mesa isolations were formed by inductively coupled plasma reactive ion etching (ICPRIE) with Cl_2-based chemistry. Source and drain contacts were formed by Ti-based metals with subsequent annealing in N_2 ambient at 750 °C for 1 min. A 5-nm-thick La_2O_3 layer was deposited by electron-beam evaporation at room temperature and a W gate electrode was *in situ* deposited using RF magnetron sputtering and patterned by ICPRIE. The reason for selecting W gate electrode is that sputter deposited layer contains sufficient amount of oxygen species, which annihilate a part of the oxygen defects in the La_2O_3 layer [12]. Annealing processes were carried out in forming gas (H_2/N_2 = 3%:97%) ambient at various temperatures. For comparison, W Schottky gated HEMT was also fabricated with identical process flow except for the La_2O_3 deposition. Electrical measurements were conducted on HEMTs with channel length (L) and channel width (W) of 25 and 100 μm, respectively, using Agilent 4156C semiconductor parameter analyzer and E4980A LCR meter for current and capacitance measurements, respectively. To analyze the chemical bonding states at the interface of La_2O_3 layer and AlGaN surface, a hard X-ray photoelectron spectroscopy (HX-PES) at SPring-8 BL46XU with an X-ray energy of

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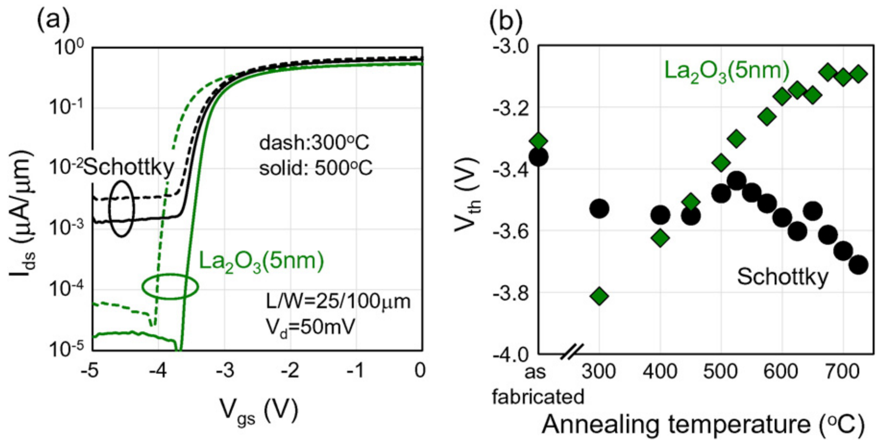

Fig. 1. (a) I_{ds}-V_{gs} characteristics of Schottky gated AlGaN/GaN HEMT and that with 5-nm-thick La_2O_3 gate dielectrics annealed at 300 °C and 500 °C. (b) V_{th} on annealing temperature shows positive shift with La_2O_3 gate dielectrics.

7940 eV was used [13]. For HX-PES analysis, the thickness of W was set to 8 nm. The surface of W layer was electrically connected to the sample plate by conductive tape, so that the Fermi level throughout the sample is constant.

3. Results and discussions

Fig. 1(a) shows gate voltage (V_{gs}) dependent channel current (I_{ds}), I_{ds}-V_{gs}, characteristics of W gated Schottky AlGaN/GaN HEMT and those with La_2O_3 gate dielectrics with drain voltage (V_{ds}) of 50 mV, annealed at 300 °C and 500 °C. HEMTs with Schottky gate show large leakage current at off-state of $V_g = -5$ V, and do not show large improvement with 500 °C annealing. The threshold voltage (V_{th}) stays almost constant around −3.5 V, which is expected from modeling including both spontaneous and piezoelectric polarizations. On the other hand, insertion of La_2O_3 reduces the off-state leakage current by two orders of magnitude, and eventually an on–off ratio of 10^5, measured at V_g of 0 and −5 V, is achieved. The sample annealed at 300 °C firstly showed negatively shifted I_{ds}-V_{gs} curve, however after annealing at 500 °C, the I_{ds}-V_{gs} curve shifted to positive direction, which is higher than that of Schottky samples. The fact strongly suggests either reaction between the La_2O_3 and AlGaN layers or creation of negative charges at the interface. The summary of the V_{th} on annealing temperature, shown in Fig. 1(b), also shows a further monotonic positive shift in V_{th} for the HEMTs with La_2O_3 dielectrics, and the overall positive V_{th} shift by 0.7 V was obtained from 300 °C annealed sample to 725 °C annealed one. In contrast, the V_{th} of W gated Schottky HEMT stayed around −3.5 V, and when annealed over 550 °C a shift toward negative direction was observed. The shift can be understood from generation of positively charged nitrogen vacancies due to reaction between W layer and AlGaN surface.

Gate-to-channel capacitance (C_{gc}) measurements at a frequency of 100 kHz, shown in Fig. 2(a), revealed a constant capacitance of 0.35 μF/cm^2 with Schottky HEMT up to 500 °C. On the other hand, W gated HEMT with La_2O_3 gate dielectrics showed a capacitance of 0.28 μF/cm^2. From the calculation of the deposited thickness of La_2O_3 layer, a dielectric constant of 10, which is quite small, can be extracted. After gradual increase in the capacitance, a further steep increase is observed starting from an annealing temperature of 525 °C, and reached to a maximum value of 0.33 μF/cm^2 at 625 °C annealing. As the temperature for the La_2O_3 film to crystallize is reported to be 500 °C, the change in the capacitance might be the increase in the dielectric constant of La_2O_3 film, where a k-value of 27 can be estimated which is quite reasonable for a pure La_2O_3 film [14]. From capacitance measurements, the effective electron mobility can be extracted and its peak values are summarized in Fig. 2(b). A higher peak mobility can be obtained with insertion of La_2O_3 gate dielectrics even at as fabricated device, which might be the protection of the AlGaN surface from damage induction during sputter deposition of W layer. A higher mobility can be preserved even after annealing, where a severe degradation can be seen with Schottky devices, suggesting creation of charged defects in the AlGaN layer.

Considering the capacitance obtained with the device annealed at 600 °C, the V_{th} value of −3.2 V is far from the calculated value of −3.8 V. Therefore, it can be considered the presence of negative charges at the interface between the La_2O_3 and the AlGaN layers. The effective

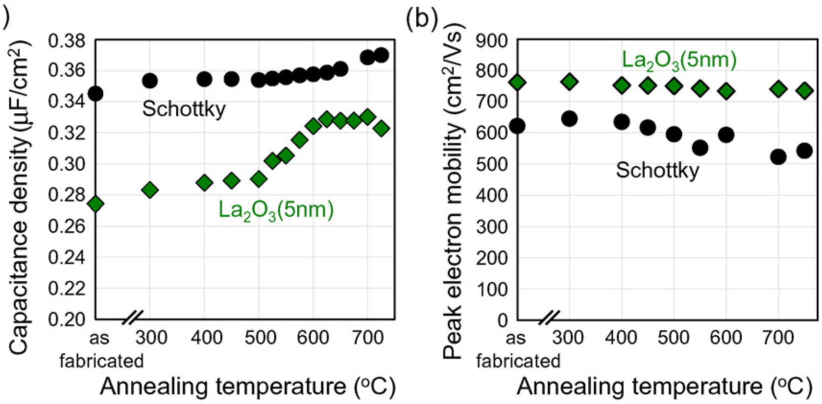

Fig. 2. (a) Capacitance of W Schottky gate HEMT and W gated HEMT with La_2O_3 gate dielectrics and (b) extracted peak electron mobility of the devices.