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Poly-Si gate electrodes for AlGaN/GaN HEMT with high reliability and low gate leakage current

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ABSTRACT

AlGaN/GaN HEMT with a BF_2-implanted polycrystalline Si gate has been characterized through comparison to TiN gate electrodes. Positive threshold voltage (V_{th}) shift was observed with the addition of F ions, which in turn degraded the effective electron mobility (μ_{eff}) by diffusion into the AlGaN/GaN interface and GaN layer. A large reduction in gate leakage current (J_g) was achieved and the property was maintained even after strong reverse-bias stressing. No additional degradation in μ_{eff} was observed, suggesting the formation of a stable poly-Si/AlGaN interface. Therefore, poly-Si gate electrodes have advantages in reducing the J_g and robustness against reverse-bias stressing.

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1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are promising candidates for next generation power devices owing to their high electron mobility with large breakdown electric field [1,2]. Due to spontaneous and piezoelectric polarizations of AlGaN and GaN layers, two-dimensional electron gas (2DEG) with a high sheet density (N_s) of over 10^{12} cm^{-2} can be achieved [3]. Ideally, a Schottky gate electrode and the 2DEG are separated by the AlGaN layer, therefore, the gate leakage current should be suppressed. However, due to the presence of defects near or at the surface of the AlGaN layer, relatively large gate leakage current is commonly observed in the devices [4,5]. These defects include etch pits which are formed during the epitaxial process and also those by interface reaction between metal and AlGaN layers by thermal treatments in the device fabrication processes. In addition, "under-gate defect" formation is reported after applying electrical stress to the gate electrodes [6].

Various Schottky electrode materials have been reported so far, including Ni, Cu, Pt, and W [7–9]. Pure metals seem to have poor thermal stability on the AlGaN layer. For instance, Ni electrodes are known to react easily with the native oxide of the AlGaN layer to form Ni-oxides at the metal/AlGaN interface, and also a diffusion of Ni atoms in AlGaN layer is observed. On the contrary, Pt electrodes show a sharp interface between metal and AlGaN layer, however, crack formations during electrical stress applications are reported due to piezoelectric strain induction. A recent study of electrode materials have revealed that the gate leakage current can be suppressed by adopting electrodes with compound nitrides [10]. Gate leakage current as well as current collapse were found to be suppressed with TiN electrodes to some extent, however, a gate material to further suppress the effects is required.

In this paper, p^+-polycrystalline Si (poly-Si) was selected as a gate electrode material, as the material has high thermal stability against agglomeration and is robust against oxidation by residual oxygen atoms in the annealing ambient [11]. Moreover, the process is compatible with conventional process and the material can be easily patterned by plasma etching equipment. In addition, F ion incorporation, which is commonly utilized to shift the threshold voltage (V_{th}) [12], can also be implemented by using BF_2 ion implantation for realizing highly doped p-type poly-Si.

2. Sample preparations

AlGaN/GaN HEMTs were fabricated on a 30-nm-thick $Al_{0.25}Ga_{0.75}N$ epitaxial layer grown on GaN channel and buffer layers on Si (111) substrates. After a mesa isolation formation by reactive ion etching (RIE) with Cl_2-based chemistry, Ohmic contacts were formed with TiN(10 nm)/Mo(35 nm)/Al(60 nm)/Ti(15 nm) multilayer deposition and subsequent annealing in N_2 for 1 min at 600 °C. An SiO_2 layer of 100 nm was deposited by atomic layer deposition (ALD) with trisdimethylaminosilane (TDMAS) and O_2 plasma exposure as a surface passivation layer. After a channel opening wet process, 30-nm-thick amorphous Si layer was deposited by electron beam evaporation at a substrate temperature of 500 °C. Then, BF_2 ion implantation with an energy and dose of 20 keV and 4.9×10^{14} cm^{-2}, respectively, were performed. The energy and dose were selected to have a projection range

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(R_p) to be at the interface of the poly-Si and the AlGaN layer, where sufficient amount of B atoms in poly-Si layer, and also in the middle of the AlGaN layer can be expected. Activation annealing was performed at 750 °C in N_2 ambient for 2 min. As a reference, an AlGaN/GaN HEMT with a TiN gate electrode with a thickness of 50 nm was fabricated as well. For the reference device, no annealing was conducted. Gate length and width of 25 and 100 μm, respectively, were used for the measurements. Schematic illustrations of the fabricated devices are shown in Fig. 1.

3. Results and discussions

Transfer characteristics of HEMTs with poly-Si and TiN gate electrodes are shown in Fig. 2, where gate leakage currents are also plotted. A positive V_{th} shift was observed with the poly-Si gated device, which is in good agreement with F-ion-treated HEMTs [12]. The off-characteristics of the TiN-gated device is mainly determined by the gate leakage current (J_g), where a high gate leakage current by 4 orders of magnitude is measured compared to those of poly-Si electrodes. Generally, the J_g depends on the properties of the AlGaN layer and the surface; nitrogen vacancies and pits and/or dislocations in the crystal [5,13]. However, as the same epitaxial wafers are used, the difference might be due to the damage creation during the reactive sputtering plasma process. The J_g at on-state ($V_g = 1$) also showed reduction by 2 orders of magnitude with the poly-Si gate electrode. Therefore, poly-Si gate electrodes are effective in reducing the J_g in both on and off-states.

Effective mobility of electrons (μ_{eff}) on N_s, shown in Fig. 3, revealed degradation in the lower carrier density range, suggesting the presence of Coulomb scattering near the interface of AlGaN and GaN layers [14]. Secondary ion mass spectroscopy (SIMS) measurements of a sample with the same structure after annealing, shown in Fig. 4, revealed the presence of F ions distributing in the AlGaN layer and some of them exist in the GaN layer. The distribution of B atoms showed fairly nice agreement with as-implanted simulation profile, therefore, the F atoms seem to be diffused during the annealing process. Indeed, the diffusion of F atoms is reported for AlGaN/GaN structure when annealed over a temperature of 350 °C [15] accompanied by degradation in μ_{eff} [16]. Based on the above consideration, the origin of the additional scattering source can be considered to be the part of the F ions which are negatively charged in the AlGaN layers. From SIMS concentration profile with the shift in the V_{th}, 0.55% of the total F atoms in AlGaN layer can be estimated to be negatively charged. Therefore, one need to consider the effect of F ion diffusion with thermal treatment to compromise the V_{th} shift and μ_{eff} degradation.

A stress voltage to the gate electrodes, ranging from −8 to −16 V, was applied to the devices for 20 s, while applying 20 V to the drain electrode. Under this condition, a high electric field at the drain edge side of the gate electrodes is applied and electron injections from gate to AlGaN layer occur. Fig. 5 shows the change in the J_g after each stress applications, where an increase in J_g can be seen with higher stressing. When a voltage lower than −11 V was applied, a change in the leakage conduction can be seen in the V_g range of −2 to 0.5 V. As the increase in J_g is observed both in negative and positive bias regions, the creation of a novel conduction path in the AlGaN layer can be inferred. Recent analysis of Pt gate electrodes on AlGaN/GaN structure showed the presence of an interfacial layer at metal/AlGaN interface, suggesting the presence interface reaction [17]. A pit-like defect creation at the interface layer and also in the AlGaN layer is reported after reverse bias stress application, near the drain edge of the gate electrode. The fact is explained by the inverse piezoelectric stress, where additional tensile strain is applied to the AlGaN layer. In addition to the defect creation, the diffusion of Pt atoms into the pits is clearly observed. Defect creation after reverse bias stress application is also confirmed by electroluminescence (EL) study, where a strong correlation is reported between the EL intensity and J_g [18]. Although, the gate material is different from the references, the creation of pits in the AlGaN layer with electromigration of Ti atoms into the defects might be the source of the increase in the leakage current.

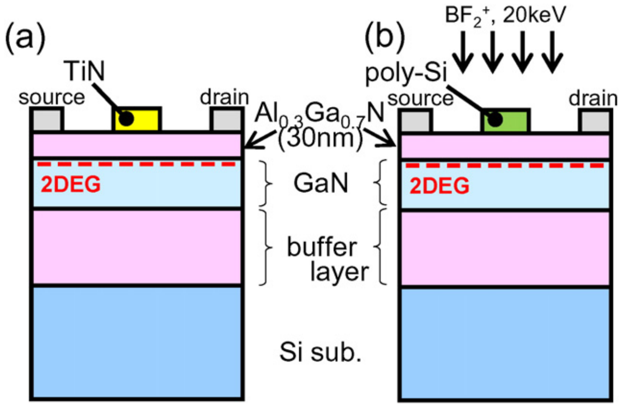

Fig. 1. Schematic illustration of the fabricated device structures: (a) TiN Schottky and (b) poly-Si gated AlGaN/GaN HEMTs.

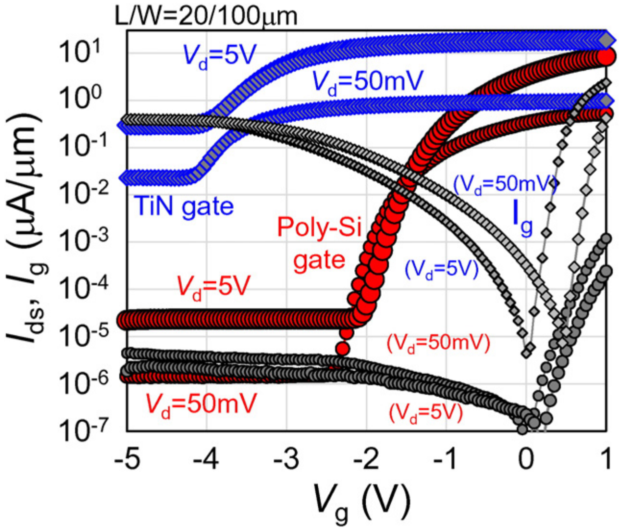

Fig. 2. Transfer characteristics of HEMT devices with poly-Si and TiN gate electrodes. A large reduction in J_g can be achieved with the poly-Si gate electrode.

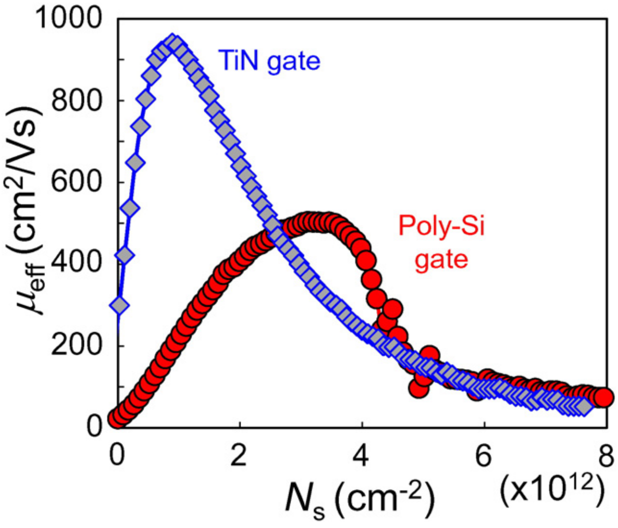

Fig. 3. Extracted μ_{eff} of both devices, showing large degradation with BF_2 implantation.

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