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Electrolyte electro-reflectance spectra of crack-free AlGaN/GaN high electron mobility transistors on Si substrate

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Abstract

A crack-free AlGaN/GaN HEMT with AlGaN graded layers was grown on Si substrate using metal organic chemical vapor deposition for the investigation of electrical characteristics employing electrolyte electro-reflectance (EER) measurements. Scanning electronic microscopy shows no crack existing and transmission electronic microscopy reveals perfect crystal quality in the HEMT structure. From EER spectra, the strength of electric field 731 KV/cm at the top AlGAN layer is determined and the sheet carrier concentration of about 1.1×10^{13} cm^{-2} is calculated. This study provides a convenient, effective and accurate method to analyze the electrical characteristics of AlGaN/GaN HEMT.

1. Introduction

The III-nitride compound materials include AlN, GaN, InN and their alloys, which has been well investigated for optoelectronic applications in both visible and ultraviolet regions [1-4]. Therefore, most groups have concentrated their effort on the fabrication of short-wavelength devices, such as light-emitting diodes and laser diodes in blue and UV regions [5]. In addition to optoelectrical devices, GaN high electron mobiligy transistors (HEMTs) have also attracted more attention for their ability of high power operation at microwave frequencies. The characteristic of high electric breakdown fields for AlGaN/GaN HEMTs ensures devices operated at high supply voltages and high operating temperature (300~500 °C) due to wide bandgap. This characteristics allow GaN based become important candidate of high power device materials [6].

Generally, the materials of III-nitride system are appropriately grown on sapphire or SiC substrates [7]. In comparison to sapphire and SiC substrates, AlGaN/GaN HEMTs grown on Si substrates have some advantages including lower cost, better device cooling and lower channel temperature [8]. However, the large degree of lattice mismatch (~17 %) and the huge difference (~37 %) in the thermal expansion coefficients between GaN and Si (111) leads severe cracks which would impact device performance. We utilized AlGaN graded layers to avoid generation of cracks and achieve good crystal quality in HEMTs. In addition to good crystal structure, it would be necessary to obtain correct information about the optical and electrical properties of two-dimensional electron gas (2DEG) for AlGaN/GaN HEMTs on Si. A 2DEG with a high mobility is induced by the high polarization discontinuity at the heterointerface, which is the important behavior for the design and performance of III-nitride devices. In this paper, a crack-free AlGaN/GaN HEMT structure with AlGaN graded layers was grown on a Si substrate by metal organic chemical vapor deposition (MOCVD) method. Scanning electronic microscopy (SEM) and transmission electronic microscopy (TEM) mainly revealed the surface morphology and layer interfaces of the samples. In addition, we proposed electrolyte electro-reflectance (EER) and Hall effect measurements which could provide a convenient and effective method to obtain the characteristics of 2DEG including electric field strength and electron concentration.

2. Results and discussions

Fig. 1 shows the TEM image with the inserted SEM image. According to the TEM image, no obvious threading dislocation exists in both AlGaN and GaN layers proving that the AlGaN graded layers could avoid effectively the generation of threading dislocations and improve crystal quality. Inserted SEM image shows a crack-free surface of the HEMT structure on Si.

To analyze the critical 2DEG at the interface of the top AlGaN and GaN layer, we carried out EER, PC and Hall effect measurement to confirm the 2DEG density more precisely. The EER spectra were measured at various external reversed dc biases from 0 to -5 V applied through a schottky gate with water as electrolyte medium, the results are revealed in Fig. 2. The EER spectra could be also probably divided into three parts. The first feature around 3.4 eV is attributed to the interband absorption of GaN layer. The second region is from 3.4 eV to 3.9 eV, a broadband signal caused by 2DEG absorption located between the GaN feature and a series of FKOs. When the reversed gate bias is low, the triangular 2DEG well in the conduction band is full of electrons, resulting in higher electron transition energy. As the reversed gate bias increases, the Fermi level is lowered and the 2DEG well is depleted which makes the electrons at the valence band are excited to the conduction band and a red shift toward the 2DEG signal marked in Fig. 2. In the region above 3.9 eV, which is contributed from the AlGaN layer, and the FKOs followed by the existence of a high electric field. This electric field strength can be evaluated precisely from analysis of the

FKOs periods. After fitted by below eq. (1) proposed by D. E. Aspnes [9], which takes the effects of light hole, heavy hole and spin orbit into consideration, we can derive the electric field on top AlGaN layer as shown in Fig. 3.

$$\frac{\Delta R}{R} \approx \sum_i \left[\frac{1}{E_n - E_g}\right] \times \exp\left[\frac{-2(E_n - E_g)^{\frac{1}{2}}\Gamma}{(\hbar\theta_i)^{\frac{3}{2}}}\right] \times \cos\left[\frac{4}{3}\left(\frac{E_n - E_g}{\hbar\theta_i}\right)^{\frac{3}{2}} + \varphi\right] \quad (1)$$

where i stands for the contribution of light hole (LH), heavy hole (HH) and spin-off (SO), respectively. As low reversed bias is applied, most of the bias voltage is consumed on the AlGaN layer while just a little part is on the AlGaN/GaN interface to deplete the band bending of GaN layer. It's clear that the electric field will be increased with increasing reversed bias. Apparently, the curve of electric field strength versus reversed bias shows linear tread, however, it gradually reaches saturated electric field due to the depletion of the 2DEG layer [10]. In Fig. 3, the electric field is estimated to be 731 KV/cm at zero bias and it reveals a saturation status which is 2753 KV/cm when reversed bias is about -1.67 V. Moreover, using the relationship between the applied gate voltage (ΔV) and the corresponding fitted electric field (ΔF), which is $d(AlGaN)=(\Delta V/\Delta F)$, thickness of top AlGaN layer could be determined to be ~20.2 nm. Meanwhile, utilizing the relationship between the maximum electric field Fth and the electric field Fb (V_{dc}) obtained at a reversed biases of V_{dc}, the electron concentration N2DEG (V_{dc}) at various reversed dc biases could be estimated by the following eq. (2) [10]. The fitted results are shown in Fig. 3 as well.

$$N_{2DEG}(V_{dc}) = \frac{\varepsilon_0 \varepsilon_{r,AlGaN}(F_b(V_{dc}) - F_{th})}{e} \quad (2)$$

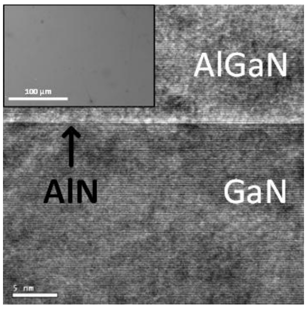

Fig. 1. Cross-sectional HRTEM of Top AlGaN, AlN and GaN layer. The arrow indicate the extremely thin AlN transition layer. The inset shows the SEM surface morphology of $Al_{0.25}Ga_{0.75}N$/GaN HEMT on Si.

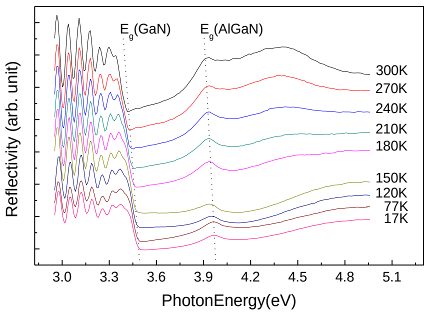

Fig. 2 Bias-dependent EER spectra with various inverse gate biases from 0 to -5 V.

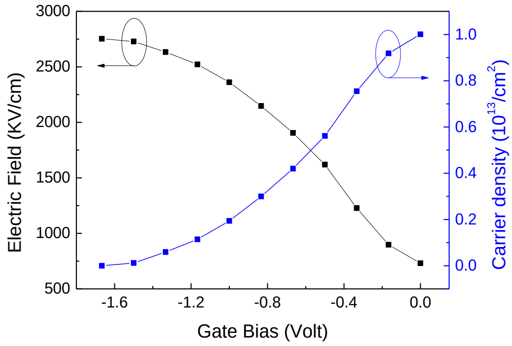

Fig. 3 Fitted results of biases-dependent EER spectra include bias-dependent electric field on top AlGaN layer and sheet electron density in 2DEG channel, respectively.

3. Conclusions

We have proposed detailed investigations for 2DEG behaviors of AlGaN/GaN HEMT on Si using a series of optical and electrical experiments. TEM and SEM observations confirm good crystal quality and crack-free characteristics for our samples. From the analysis of the FKOs observed in EER spectra under reversed biases from 0 to -1.67 V, the strength of electric field and the thickness on top AlGaN layer are determined 731 KV/cm and ~20.2 nm, respectively. This study demonstrates that EER analysis could obtain relevant information effectively about 2DEG characteristics in GaN HEMT grown on Si.

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