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Piezoelectric field in highly stressed GaN-based LED on Si (1 1 1) substrate

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ABSTRACT

Stress states in GaN epilayers grown on Si (1 1 1) and *c*-plane sapphire, and their effects on built-in piezoelectric field induced by compressive stress in InGaN/GaN multi-quantum well (MQW) light-emitting diodes (LEDs) were investigated using the electroreflectance (ER) spectroscopic technique. Relatively large tensile stress is observed in GaN epilayers grown on Si (1 1 1), while a small compressive stress appears in the film grown on *c*-plane sapphire. The InGaN/GaN MQWs of LED on c-plane sapphire substrate has a higher piezoelectric field than the MQWs of LEDs on Si (1 1 1) substrate by about 1.04 MV/cm. The large tensile stress due to lattice mismatch with Si (1 1 1) substrate is regarded as external stress. The external tensile stress from the Si substrate effectively compensates for the compressive stress developed in the active region of the InGaN/GaN MQWs, thus reducing the quantum-confined Stark effect (QCSE) by attenuating the piezoelectric polarization from the InGaN layer.

1. Introduction

The search for a substrate other than sapphire for the fabrication of nitride light-emitting diodes (LEDs) has attracted much attention since the successful fabrication of nitride LEDs. Silicon (Si) has long been an ideal candidate for obvious reasons. InGaN/GaN multi-quantum well (MQW) LEDs grown on Si substrates have a number of advantages over those grown on c-plane sapphire substrates [1], including the relative low cost of large diameter Si (1 1 1) wafers and the existence of well-developed Si removal processes that could be employed to drive down the cost of LED manufacture. Moreover, the high conductivity of Si substrate means that ohmic contacts can be formed directly on the back side, which provides an easier LED fabrication technique than the traditional process on sapphire substrate [2–5]. However, LED-on-Si wafers grown using metal organic chemical vapor phase deposition (MOCVD) often exhibit a high level of tensile stress in the III-nitride epitaxial layers due to their lattice and thermal mismatch with the Si substrate, which can lead to cracking of the nitride layer during cooling to room temperature or in subsequent LED fabrication processes. The tensile stress in the nitride can be relieved to some extent by introducing a strategic wafer bow in the substrate. On the other hand, the conventional InGaN/GaN MQW LEDs epilayers grown on a *c*-plane sapphire substrate have a high level of compressive stress caused by the difference in the large lattice mismatch and thermal expansion coefficient between the epitaxial layers and the substrate [6]. Both tensile stress and compressive stress affect the performance of optoelectronic devices [7,8]. A number of approaches for controlling wafer bow and reducing stress in GaN layers on Si and/or sapphire substrates have been reported [9–15]. Nevertheless, the particular interest to both the scientific community and the device manufacturers is the influence of very large polarization fields in the InGaN/GaN MQW active region, whether grown on Si or on sapphire substrates [16]. The existence of a piezoelectric field in InGaN/GaN QWs, induced by the compressive stress arising from the pseudomorphic growth of $In_xGa_{1-x}N$ on GaN, leads to not only shifts in the emission wavelength associated with the quantum-confined Stark effect (QCSE) but also a reduced emission efficiency due to the separation of electron and hole wave functions in the quantum well (QW). Furthermore, the band bending induced by the polarization field in the QWs increases the carrier loss and thus decreases the radiative recombination efficiency as the current increases [17–21]. The exact measurement of the piezoelectric field has been attempted by using different spectroscopic methods: photo-luminescence (PL), electro-transmission (ET), electro-reflectance (ER), and photocurrent (PC) [22–27]. In this study, the stress state of GaN films

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grown on Si (1 1 1) and c-plane sapphire substrates were compared. The dependence of the piezoelectric field in the InGaN/GaN MQW active region on the stress states of GaN films in the two LED structures is measured by using the ER spectroscopic method. The ER spectra from the InGaN/GaN MQW active region prepared on Si (1 1 1) and c-plane sapphire substrates is measured with different reverse voltages. The piezoelectric field in the InGaN QWs was estimated from the observed blue shift of the InGaN QWs spectral line with increasing reverse voltage. To exactly determine the piezoelectric field in the QWs, we also performed capacitance-voltage measurements and estimated the depletion layer width, which is the main voltage drop region in our sample structures.

2. Experimental

Conventional blue LEDs were grown on Si (1 1 1) and c-plane (0 0 0 1) sapphire substrates in a MOCVD system. Metalorganic compounds of TMGa, TMIn, TMAl, and NH_3 were used as the reactant source for Ga, In, Al, and N, respectively. The LED structure grown on Si (1 1 1) substrate consisted of a 180-nm-thick AlN seed layer, an 800-nm-thick AlGaN step-graded buffer layer, a 1.5-μm-thick unintentionally-doped GaN layer, and a 1-μm-thick Si-doped n-type GaN layer. Four periods of the InGaN/GaN MQW active regions were then grown on the n-GaN. Finally, a 20-nm-thick p-AlGaN and a 120-nm-thick highly doped p-GaN were grown in the normal sequence. The LED structure grown on the c-plane sapphire substrate consisted of a 30-nm-thick GaN nucleation layer (which was grown on the sapphire substrate), a sequentially grown 2-μm-thick undoped buffer GaN layer, and a 3-μm-thick Si-doped n-type GaN layer. Then, five periods of InGaN/GaN MQW active regions made from a 2.4-nm-thick undoped InGaN quantum well (QW) layer and a 7.2-nm-thick GaN quantum barrier (QB) layer were grown on the n-GaN. Finally, a 40-nm-thick p-AlGaN and a 70-nm-thick highly doped p-GaN were grown in the normal sequence. Fig. 1 shows schematic structures of the two fabricated LEDs.

After forming the two LED structures, the samples were fabricated using the conventional standard process with 1000 μm × 1000 μm and 600 μm × 1100 μm chip dimensions for LEDs grown on Si (1 1 1) and c-plane sapphire substrates, respectively. We then used a scribe and break method to fabricate GaN-based LED chips. The bending displacement of 30 LED chips was measured using a 3D surface profiler for these two fabricated LED structures, and the median value was found. The substrate curvature of each LED structure was calculated from the bending displacement and the chip dimensions. The relation between the epilayer stress and substrate curvature is given by Stoney's equation [28].

LED chips without epoxy were prepared on a surface mounted device (SMD) package for ER measurements. The ER experiment was performed at room temperature. The sample was illuminated by a 150 W Xe-Arc lamp combined with a 0.25 m dual-grating monochromator for a probe beam. The probe beam was used to illuminate vertically on the sample, with a wavelength resolution of 0.007 nm. The internal electric field was modulated by a function generator. A modulation voltage of 100 mVpp at 1 kHz was applied to the sample. The bias voltage was changed within the range of from 0 V to −12 V, so there was no injection of carriers through the p-n junction. The reflected beam was detected using a photomultiplier tube. The ac component [I(λ)ΔR(λ)] and dc component [I(λ)R(λ)] were measured using a lock-in amplifier and a dc meter, respectively. ΔR/R was obtained by dividing the ac component by the dc component. In addition, the capacitance-voltage (C-V) measurements were taken at room temperature to measure the depletion width.

3. Results and discussion

Fig. 2(a) shows the dependence of the bowing curvature of the Si (1 1 1) and c-plane sapphire substrates and the corresponding residual mechanical stress in the grown GaN layer according to the substrate type. For the GaN film grown on a Si (1 1 1) substrate, it was observed that the average measured curvature of the bowing was about 2.79 m^{-1} and the curvature was concave. This concave curvature of the GaN epilayers is due to the residual tensile stress. For GaN epilayers grown on the c-plane sapphire substrate, the bowing curvature was about 3.42 m^{-1} in the convex direction due to the residual compressive stress. It was also observed that relatively large tensile stress (∼0.73 GPa) exists in the GaN epilayers grown on Si (1 1 1) compared to the compressive stress (∼−0.62 GPa) observed in the film grown on c-plane sapphire. The reason why the stress states in the GaN epilayers grown on Si (1 1 1) and on c-plane sapphire are opposite can be easily explained. For the GaN/Si (1 1 1) system, the lattice constant of GaN is smaller than that of Si (1 1 1) and its thermal expansion coefficient is larger than that of Si (1 1 1). Both lattice and thermal mismatches lead to tensile stress in the GaN epilayer. For the case of the GaN/c-plane sapphire, it is known that the epitaxial GaN

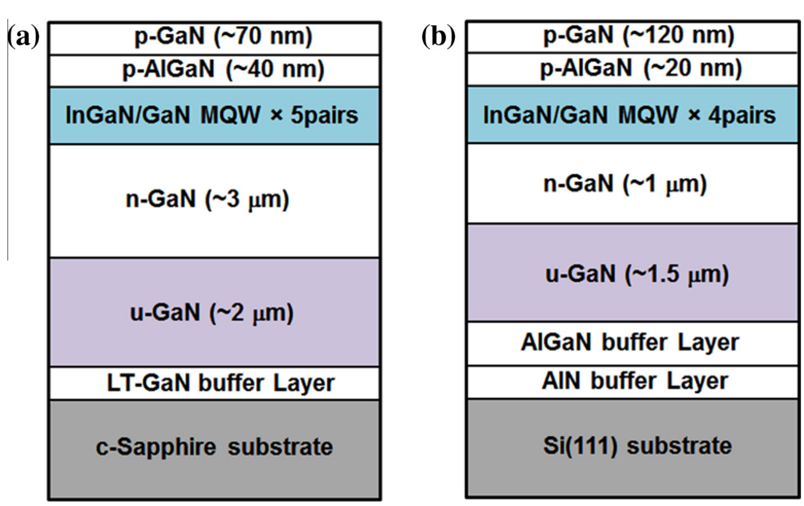

Fig. 1. Schematic structures of the two fabricated LEDs. (a) LED grown on c-plane sapphire substrate. (b) LED grown on Si (1 1 1) substrate.