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Stress relaxation in GaN by transfer bonding on Si substrates

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The stress state of GaN epilayers transferred onto Si substrates through a Au–Si bonding process was studied by micro-Raman scattering and photoluminescence techniques. By increasing the Au bonding thickness from 1 to 40 μm , the high compressive stress state in GaN layer was relieved. A 10 μm Au bonding layer thickness is shown to possess the maximum compressive stress relief and also the deformation potential of the quantum well was found to be ~ 85 meV. A nonlinear parabolic relation between luminescent bandgap and the biaxial stress of the transferred GaN epilayer in the compressive region was observed. © 2007 American Institute of Physics.

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GaN-based semiconductors have attracted great attention for application in solid-state lighting due to its robustness and the tenability of emission wavelengths and characteristics. Metal-organic chemical vapor deposition (MOCVD) GaN light emitting diode (LED) epilayers are typically grown on sapphire substrates due to cost. However, several drawbacks to this architecture are encountered, especially when considering the need for optimizing heat dissipation, limiting defects in the device, and improving light output. On the other hand, thin-GaN LED architectures have proven to possess better electrical and optical properties over the traditional wire-bonded GaN on sapphire LED schemes. To achieve thin-GaN LEDs for the general illumination, the initially grown GaN epilayer is transferred onto other substrates with lower thermal conduction resistances. Many different approaches can be utilized to transfer the original MOCVD GaN epilayer onto the thermally conductive substrates. Of these methods, the most promising one for GaN epilayer transfer involves wafer bonding followed by laser lift-off techniques.^{1–4}

MOCVD GaN epilayers on the sapphire substrates are known to have a high compressive stress due to the large lattice mismatch and process-induced thermoelastic effects from the coefficient of thermal expansion mismatch between sapphire substrate and GaN.^{5,6} The compressive stress will cause the distortion of energy bandgap and the charge separation in the quantum wells. During the operation of GaN LED devices, the internal piezoelectric field is also normal to the quantum well plane and induces quantum-confined stark effects (QCSE). As a result of intrinsic stresses and QCSE, two effects are seen which can impact the performance of the transferred GaN devices. The first effect is a redshift in emit-

ted light at increasing forward current injection. The second effect is the degradation of external quantum efficiency.⁷ We believe that the distortion of the GaN energy band structure from induced stresses will strongly affect the LED device performance such as the recombination efficiency, emission peak wavelength, and threshold current. In this work, we explore the impact of the stress state in transferred GaN devices on the performance of thin-GaN LED devices to better elucidate the impact of the transfer process on device behavior.

AlInGaN multiple quantum wells (QWs) LED epilayer structures were grown on a sapphire substrate by MOCVD. Then, a Ni/Au *p*-GaN contact layer was deposited on the *p*-GaN layer by e-beam process and followed by an annealing process to achieve a low-resistance contact. The annealing temperature was 500 °C for 2 min in air. To facilitate the thin-GaN structure, a reflective layer of Al was utilized to reflect the downward emitting light through the top *p*-type contact. After the Al reflection layer deposition, the bonding metallization, Ni/Au, was deposited on the top of the Al layer. Ni serves as an adhesion and barrier layer and the Au layer is used for the Au–Si wafer bonding.

A bonding Au layer was deposited on the transferring Si substrate. The thickness of Au layer varied from 1 to 40 μm . A heavy doped (111) Si (P^+ , 10^{-3} Ω cm, 525 μm) was used to bond with the GaN wafer. The Si wafer was cleaned by standard acid solutions to ensure the cleanliness of the Si bonding surface. To perform the wafer bonding process, a commercial wafer bonder (EVGroup, model 501) was used. The bonding temperature and pressure were 420 °C and 5 MPa, respectively. The bonding time was 20 min.

After the GaN/Si bonding, a KrF excimer laser (JPSA-IX120i, 248 nm, 25 ns) was used to strip the initial sapphire substrate through the laser lift-off method. The laser pulse

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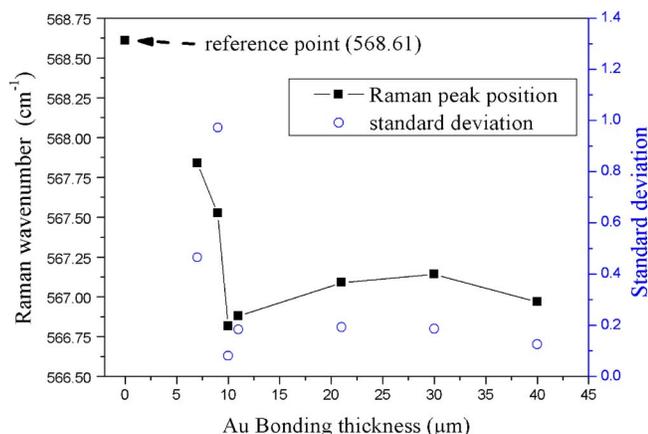


FIG. 1. (Color online) The Raman peak position vs Au bonding layer thickness.

was focused onto the interface of the GaN and sapphire substrate with high enough energy to induce a thermal decomposition reaction in the GaN near the interface. By scanning the GaN-sapphire interface, the GaN epilayer was separated from the sapphire substrate and transferred onto the Si substrate. During the wafer bonding process, the GaN epilayer remained connected to the sapphire and under compressive stress. At the bonding temperature (over 400 °C), a eutectic Si/Au liquid alloy formed at the bonding interface. Therefore, the Si substrate has no influence on the stress state of GaN on sapphire at the bonding temperature. While the temperature cooled below the solidification point of the eutectic Au-Si composition (363 °C), the effect of transferring to the Si substrate started showing its influence on the stress state of GaN on sapphire. As the temperature cooled to room temperature, the difference in thermal expansion coefficients and elastic properties of the Si and GaN have to be taken into account in order to predict or understand the final stress state of GaN on sapphire. To experimentally evaluate the biaxial stress state of GaN, Raman spectroscopy was used to analyze the transferred GaN epilayer on Si substrate. A Renishaw InVia Raman microscope with 180° backscattering geometry and 488 nm Ar⁺ laser was used for all measurements in this study. With a spectrometer focal length of 250 mm and a diffraction grating of 3000 lines/mm, a spectral dispersion of 0.46 cm⁻¹/pixel was obtained at a slit width of 50 μm. This provided a resolution able detect Stokes peak shifts within ±0.057–0.1 cm⁻¹ from Voigt fits of the isolated Si Raman line. A 50× objective with a numerical aperture of 0.5 was used to focus the probe laser beam and collect the Raman signature of the samples. By analyzing the Raman shift (E2 mode), the stress level of the transferred GaN epilayer were obtained.

Figure 1 shows the Raman peak position of the transferred GaN epilayer with various Au bonding thicknesses ranging from 7 to 40 μm. The Raman peak position of the MOCVD GaN layer on sapphire is 568.61 cm⁻¹. We found that the Raman peak position of the transferred GaN epilayer has a redshift to the short wavenumber region. In addition, with the increasing Au thickness, the larger redshift of the Raman peak position was observed. The redshift of the Raman peak position implies the release of the compressive stress state in the GaN epilayer. Kozawa *et al.* calibrated the effect of biaxial stress levels in GaN with the measured Raman shift ($\Delta\omega$), showing the following relationship: $\Delta\omega$

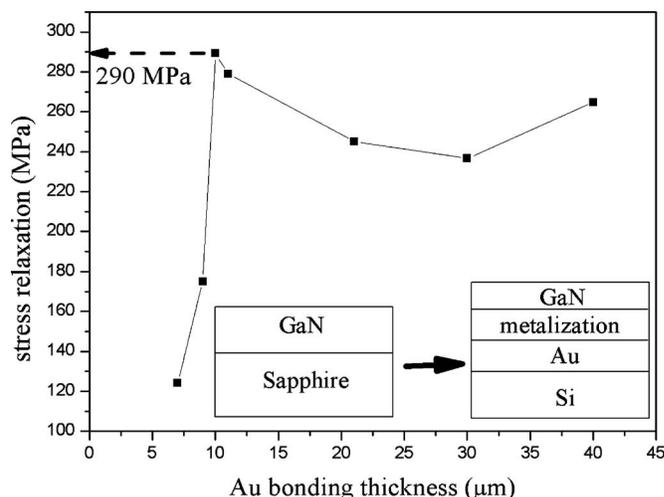


FIG. 2. The stress relaxation vs Au bonding layer thickness.

$=6.2\sigma_{\text{GaN}}$.⁵ By using this relationship, the stress state of the GaN epilayer can be obtained directly from the shift in the peak of the Raman Stokes signal, provided that the Stokes peak position under no stress is known. This value is typically considered to be 567 cm⁻¹ for unstressed GaN. Figure 2 shows the magnitude of the stress relaxation versus the Au bonding thickness. The maximum compressive stress relief in the transferred GaN thin film occurred at the largest Raman peak position shift of 10 μm Au layer (redshift in the Stokes peak of 1.79 cm⁻¹). The maximum compressive stress relief is observed to be around 290 MPa. Remarkably, as the thickness of Au bonding layer increases over 10 μm, the tensile stress level of the transferred GaN epilayer starts decreasing slightly.

Low temperature photoluminescence (PL) spectra were obtained by a PL system with 325 nm He-Cd laser as excitation light source. PL measurement is then used to analyze the luminescent bandgap change with various stress level in the transferred GaN epilayer on Si. The relationship between bandgap and stress relaxation level of the transferred GaN epilayer are shown in Fig. 3. As expected, the energy bandgap increases due to the relief of the compressive stress. By the study of Takeuchi *et al.*,⁸ the built-in piezoelectric field

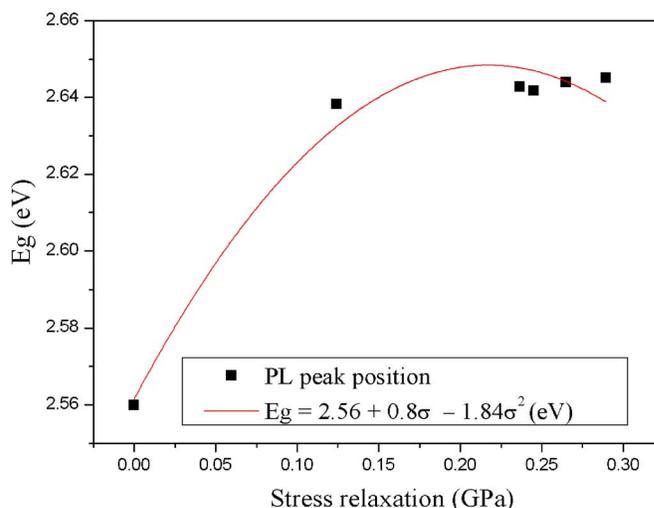


FIG. 3. (Color online) The relation between Energy bandgap and stress relaxation of the transferred GaN epilayer.

will lead to QCSE and a smaller effective bandgap. According to their calculation that the strain-induced piezoelectric field in the case of the 13% indium content induces a redshift of about 240 meV for the 5 nm thick quantum well, i.e., the deformation potential of GaN (the relation between the piezoelectric field parallel to the c axis and the bandgap energy) was found to be 240 meV. In our case, 85 meV was estimated to be the largest blueshift observed as the internal strain was relieved. It is expected that this blueshift will contribute to the decrease in QCSE. By controlling the stress state in the transferred GaN thin film, we can change the built-in piezoelectric field and alleviate the QCSE to further improve the lighting performance. Unlike the linear relation in the tensile region of the GaN layer reported by Zhao *et al.*,⁶ we found a nonlinear parabolic dependence of the QW bandgap with the stress level $E_g=2.56+0.8\sigma-1.84\sigma^2$ (eV). A linear relationship with a linear coefficient of 21.1 ± 3.2 MeV/GPa was reported in their experiments. This effect will compete with the blueshift phenomena induced by piezoelectric field change.

In summary, the transferred GaN epilayer on Si substrates was characterized by Raman spectroscopy measurements to determine its impact on the state of stress in the thin GaN structure. The transfer of GaN films to Si substrates resulted in a favorable relief in biaxial compressive stresses which were present from the growth on sapphire substrates. A parabolic relationship between the energy bandgap and the

stress state of the transferred GaN epilayer was observed, and the relation was expressed by $E_g=2.56+0.8\sigma-1.84\sigma^2$ (eV). These results show that the thermoelastic stress effects in thin GaN LED devices can be controlled through transfer processing methods and can result in an impact on overall device performance and efficiency.

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