GaN/metal/Si heterostructure fabricated by metal bonding and laser lift-off *

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Abstract: A process methodology has been adopted to transfer GaN thin films grown on sapphire substrates to Si substrates using metal bonding and laser lift-off techniques. After bonding, a single KrF (248 nm) excimer laser pulse was directed through the transparent sapphire substrates followed by low-temperature heat treatment to remove the substrates. The influence of bonding temperature and energy density of the excimer laser on the structure and optical properties of GaN films were investigated systemically. Atomic force microscopy, X-ray diffraction and photoluminescence measurements showed that (1) the quality of the GaN film was higher at a lower bonding temperature and lower energy density; (2) the threshold of the energy density of the excimer laser lift-off GaN was 300 mJ/cm^2. The root-mean-square roughness of the transferred GaN surface was about 50 nm at a bonding temperature of 400 °C.

Key words: GaN films; silicon; metal bonding; laser lift-off; atomic force microscopy; X-ray diffraction
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1. Introduction

Gallium nitride (GaN) materials and devices have been intensively studied. As the material quality of GaN has improved, the prospects for heterogeneous integration of GaN devices with host substrates are of interest. Due to the lack of bulk large-area GaN substrates, GaN thin films are deposited on available dissimilar substrates such as sapphire and silicon carbide (SiC). Sapphire is one of the promising substrates for GaN-based materials because of its high-temperature stability, similar crystal symmetry to the III-nitrides, and relatively low cost. However, it still imposes constraints on the GaN film quality due to the lattice and thermal-expansion coefficient mismatch between sapphire and GaN. Furthermore, the poor thermal conductivity of sapphire prevents efficient dissipation of the heat generated by GaN-based high-current devices, especially in high-power transistors and laser diodes (LD). Because of the poor electrical conductivity of sapphire, all contacts of the GaN-based devices must be made from the top side. This configuration complicates contact and packaging schemes, resulting in a spreading-resistance penalty and increased operating voltages[1].

The inherent sapphire constraints have spurred interest in integrating GaN-based materials with Si substrates by direct growth of GaN on Si[2,3]. However, direct deposition of III-nitride-based thin films on Si substrates presents significant challenges due to the large mismatch in lattice constants (~20%) and thermal expansion coefficients (2.6×10^{-6} K^{-1} for Si and 5.6×10^{-6} K^{-1} for GaN), and their properties are still poorer than those grown on sapphire, the more widely used substrate. A more viable means of integrating GaN thin films with dissimilar materials is through wafer-bonding and thin-film lift-off techniques. The laser lift-off (LLO) technique has been demonstrated to successfully separate GaN thin films from sapphire substrates. Since Kelly *et al.*[4] reported pulse laser-assisted thermal etching of GaN using the third harmonic of a Q-switched Nd:YAG laser with 355-nm wavelength in 1996, many experiments have been performed to develop the LLO technique[5–8]. Wong *et al.*[9,10] have reported a process to separate the thin film GaN-based device using a laser separation technique that decomposes the interface between the GaN and the sapphire substrate. Such approaches will allow for integration of high-quality GaN-based optoelectronic devices, pre-fabricated on sapphire substrates, with other substrate materials.

In this paper, a band gap-selective LLO technique in conjunction with metal bonding is utilized to integrate GaN thin films with Si substrates. The influence of bonding temperature and energy density of the excimer laser on the structure and optical properties of GaN thin films are investigated systemically.

2. Experimental procedure

The GaN thin films (~1 μm) in this study were grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. The p-Si substrates were treated by standard Radio Corporation of American (RCA) cleaning. Ni/Au (40

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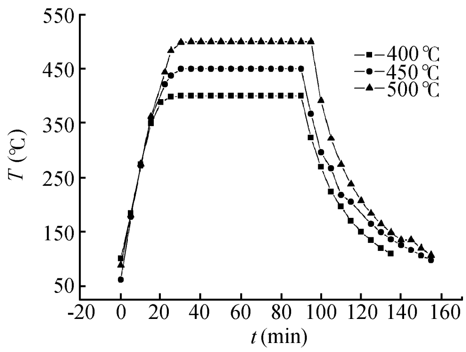

Fig. 1. Annealing curve of the wafer bonding.

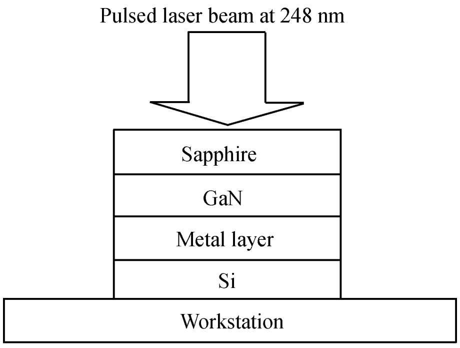

Fig. 2. Schematic illustration of the laser lift-off of GaN thin film.

nm/200 nm) was deposited on the surfaces of GaN, while Ti/Au (40 nm/200 nm) was deposited on the clean Si substrate. Then the structures were stacked face to face. The bonding process was carried out in nitrogen ambient at 400, 450 and 500 °C for 1 h. The annealing curves are shown in Fig. 1.

The LLO processing of the sapphire/GaN/Ni/Au-Au/Ti/Si structure was performed in air using a Lambda Physik Lextra 248 nm KrF pulsed excimer laser (25 ns pulse duration). At such wavelength, the sapphire substrate is transparent and the radiation is absorbed by a thin GaN layer with a thickness of about 200 nm at the GaN/sapphire interface[11]. The samples were placed on the top of the working station which can be moved in 0.8 mm steps to scan a typical sample size of 1×1 cm^2 using a computer-controlled stepper motor. The laser beam was focused onto an approximate 1 mm^2 spot by a silica convex lens with a focal length of 80 cm to scan over the wafer with a speed of 5 mm/s. The laser fluence was varied from 250 to 325 mJ/cm^2 at a constant number of pulses. After laser irradiation, the GaN sample tended to show some material residues, such as Ga and Ga oxide. By melting the thin metallic Ga interfacial layer (T_M = 30 °C) after laser irradiation, the GaN thin film was transferred from the sapphire substrate to the Si substrate. A schematic diagram of LLO is shown in Fig. 2.

3. Results and discussion

Using metal bonding and LLO, large area GaN thin films were successfully transferred from sapphire substrates to Si substrates with bonding temperature of 400, 450 and 500 °C.

To optimize the laser power, the amount of decomposed

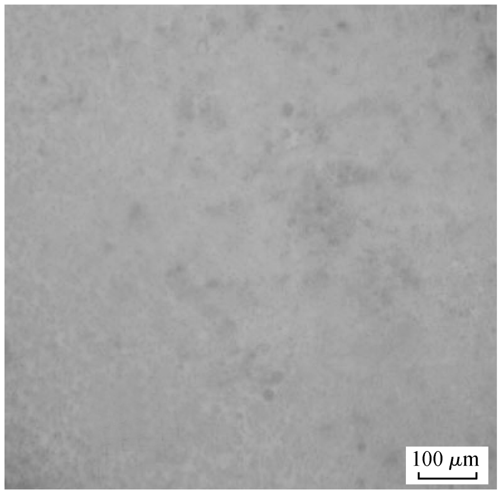

Fig. 3. Optical microscopy image of the GaN film after LLO.

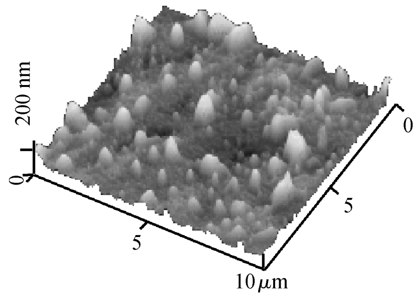

Fig. 4. Atomic force microscopy image of the GaN film after LLO.

GaN due to a single laser pulse was investigated, using a KrF excimer laser, as a function of laser energy density from 250 to 325 mJ/cm^2. The laser irradiation causes the decomposition of GaN into gaseous nitrogen and gallium droplets, following the equation:

$$\mathrm{GaN} \Leftrightarrow \mathrm{Ga} + \frac{1}{2}\mathrm{N_2}\,(\mathrm{g}).$$

The decomposition of the GaN material is attributed to the absorption of photon energy, which produces local heating at the GaN/sapphire interface[12]. Chu *et al.*[13]showed that GaN breaks down into metallic Ga and gaseous nitrogen when the local temperature exceeds 1000 °C during the laser illumination process. Our study shows that no detectable material removal is observed when the laser energy density falls below 275 mJ/cm^2. With increasing energy densities, some metallic Ga droplets are observed at the interfacial region. When the incident fluence is up to 300 mJ/cm^2, a metallic silver color is clearly observed at the interface of GaN and sapphire, indicating the decomposition of the GaN interfacial layer between GaN and sapphire. Based on the laser etching of the GaN sample, we obtained the threshold laser fluence for ablation of the GaN surface to be about 300 mJ/cm^2.

The GaN thin films before bonding and after laser irradiation were characterized by optical microscopy, atomic force microscopy (AFM), X-ray diffraction (XRD) and photoluminescence (PL) spectra.

Figure 3 shows a typical optical microscope image of the GaN films after laser irradiation. The surfaces of most of the samples after LLO were relatively flat. Figure 4 shows a typi-

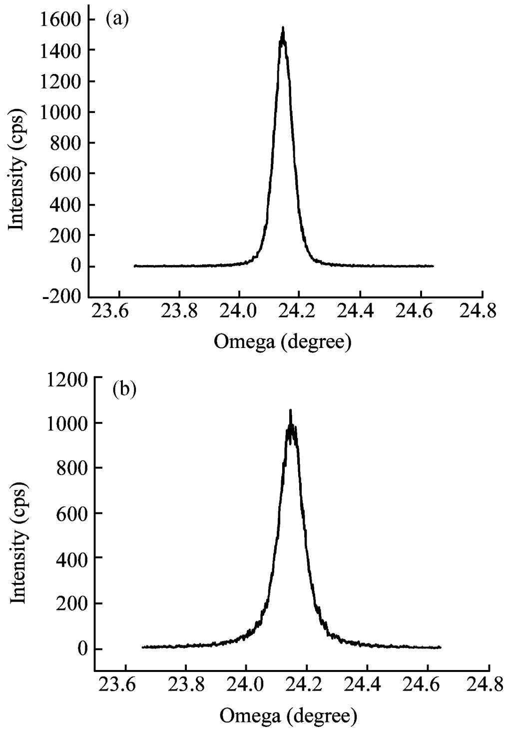

Fig. 5. X-ray diffraction spectra of the GaN sample: (a) Before laser lift-off; (b) After laser lift-off.

cal AFM image of the GaN film on Si after LLO. Uneven structures were formed as the result of the lift-off process. The root-mean-square (RMS) surface roughness is around 50 nm, which is comparable with the value reported by Wong *et al.*[14]. Further optimization of the lift-off condition would improve the flatness. Compared with the conventional GaN surface asperity method, LLO is more efficient and simple. For GaN-based LEDs, the surface asperity of GaN may potentially lead to a significant improvement in the light extraction efficiency of the LEDs[15].

XRD is the standard nondestructive method to characterize the structural quality of crystals. Figure 5 shows a typical XRD spectrum of the GaN sample (bonding temperature 500 °C, laser energy density 325 mJ/cm^2) before bonding and after lift-off. The full-width at half-maximum (FWHM) of the LLO film is about 0.086 degrees, which is slightly larger than that of the as-grown GaN film, 0.062 degrees. The increase in the FWHM of the rocking curve may be due to the thermally induced lattice disorder carried by the laser irradiation. Combined with the RMS value measured by AFM, we found that the lower bonding temperature and laser energy density have less effect on the crystal quality of the samples.

Typical PL spectra for the original GaN and GaN after lift-off are shown in Fig. 6. It is observed that the sample (bonding temperature 500 °C, laser energy density 325 mJ/cm^2) after LLO shows a red shift in the PL relative to that of the sample grown on sapphire. This is likely due to the relaxation of the residual strain in the de-bonded GaN films, as the as-grown films on sapphire substrates are typically under compressive strain. After Gaussian fitting, it is found that the

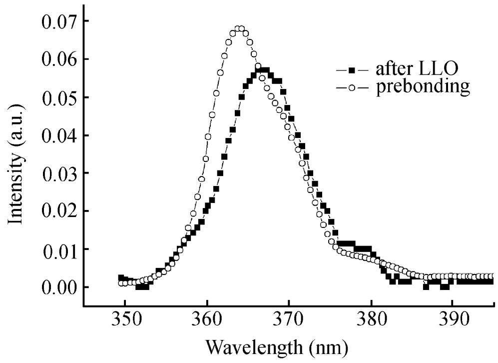

Fig. 6. PL spectra of GaN film before and after laser lift-off.

FWHM of the sample grown on sapphire substrate was 9.3 nm, while after LLO, the FWHM of the sample transferred to Si substrate was 10.3 nm. The interfacial-layer linewidth broadening may be solely attributed to the high density of extended defects commonly found at the GaN/sapphire interface and not to the damage induced by the LLO process[14]. The PL spectra of GaN thin films on sapphire and on Si at room temperature confirm that metal bonding and the LLO technique have less effect on the optical quality of the GaN films.

4. Conclusions

In summary, GaN thin films grown on sapphire substrates were successfully transferred to Si substrates using a combination of metal bonding and LLO processes. The threshold of the energy density of the excimer LLO GaN was 300 mJ/cm^2. The AFM measurement showed that the surface of GaN was uneven after LLO and the RMS roughness of the surface of GaN films on Si was about 50 nm. XRD and PL measurements showed that the structural and optical performance of the thin film was less affected by the metal bonding and LLO process. It is feasible to integrate high-quality GaN-related optoelectronic devices with Si substrates with this technique.

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