Integration of GaN thin films with silicon substrates by fusion bonding and laser lift-off

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GaN thin films grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD) are successfully bonded and transferred onto Si receptor substrates using fusion bonding and laser lift-off (LLO) technique. GaN/Al_2O_3 structures are joined to Si substrates by pressure bonding Ti/Au coated GaN surface onto Ti/Au coated Si receptor substrates at the temperature of 400 °C. KrF excimer laser with 400-mJ/cm^2 energy density, 248-nm wavelength, and 30-ns pulse width is used to irradiate the wafer through the transparent sapphire substrates and separate GaN films from sapphire. Cross-section scanning electron microscopy (SEM) combined with energy dispersive X-ray spectrometer (EDS) measurements show that Au/Si solid solution is formed during bonding process. Atomic force microscopy (AFM) and photoluminescence (PL) measurements show that the qualities of GaN films on Si substrates degrade little after substrates transfer.

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GaN-based light-emitting diodes (LEDs) can be widely used in full-color displays, high efficient and reliable green traffic lights, flat-panel room lighting to replace incandescent and fluorescent fixtures, and many other fields[1,2]. At present, GaN-based LEDs are mostly deposited on sapphire with hexagonal wurtzite crystal structures matching GaN well[3−6]. But the large lattice parameter mismatches impede the quality and thickness of GaN films. The poor electrical and thermal conductivity of sapphire substrates complicates the device process and imposes many other significant performance constraints on GaN-based LEDs[7−9].

Laser lift-off (LLO) in conjunction with wafer bonding technique can efficiently realize transferring GaN-based LEDs from sapphire to other receptor substrates with high electrical and thermal conductivity, such as Si and Cu, by which the vertical-structure GaN-based LEDs can be fabricated. Since Kelly et al. reported the pulse laser-assisted thermal etching of GaN using the third harmonic of a Q-switched Nd:YAG laser with 355-nm wavelength in 1996 for the first time[10], many experiments have been performed to develop the LLO technique[11−13]. To support and protect the GaN LEDs structures from fracture during LLO, the bonding layer must be uniform. To avoid constraining the performance of the vertical-structure GaN-based LEDs, bonding materials must have low electrical resistance and the bonding process should be performed at a low temperature. Wong *et al.* has reported integration of GaN thin films with Si substrates by Pd-In metal bonding at the temperature of 200 °C[14]. For this technique, the ratio of metal Pd to In should be controlled precisely to 1:3 to form $PdIn_3$. Chu *et al.* used metal In as the bonding material[15]. Using In, dry etching process instead of HCl solution should be adopted to remove the residual Ga, because the etching rate of metal In in HCl solution is also high. Besides, these methods need additional deposition of the integration materials, which complicates the process of GaN-based LEDs.

In this paper, thin GaN films (instead of GaN LEDs for predigestion) are successfully transferred from sapphire substrates to Si receptor substrates using LLO combined with Au/Si fusion bonding technique. Ti/Au, the component of high reflector mirror used in conventional GaN-based LEDs, serves as the bonding metal at the same time, needing no additional deposition process. Scanning electron microscopy (SEM) and energy dispersive spectrometer X-ray spectrometer (EDS) measurements show that the compact Al_2O_3/ GaN/Ti/Au/Au/Ti/Si structures are formed at the temperature of 400 °C. The atomic force microscopy (AFM), photoluminescence (PL) measurements show that the properties of GaN films change little after being transferred to Si substrates using LLO and fusion bonding technique.

Undoped GaN thin films (∼ 4 μm) are grown on sapphire (0001) substrates by metalorganic chemical vapor deposition (MOCVD) at a pressure of 0.027 MPa. Trimethylgallium (TMG) and ammonias (NH_3) are used as sources of Ga and N, respectively. After deposition, the backside of sapphire is polished and thinned to 100 μm using diamond slurries with the size less than 500 nm to reduce the ultraviolet (UV) pulse laser absorption and reflection of sapphire substrates during laser irradiation. Ti/Au (10 nm/800 nm) is deposited on the surfaces of GaN and Si by electron beam evaporation. GaN/Al_2O_3 structures are then bonded onto Si at 400 °C at the pressure of 5×10^4 Pa for 30 min in a flowing nitrogen ambient forming the Al_2O_3/GaN /Ti/Au/Au/Ti/Si structures. The final structure of the samples is shown in the inset of Fig. 1.

The uniformity of the initial KrF excimer laser (LPX 150) with 248-nm wavelength and 30-ns pulse width is improved by echelon-free induced special incoherence (EFISI) technique[16]. The energy distribution of the

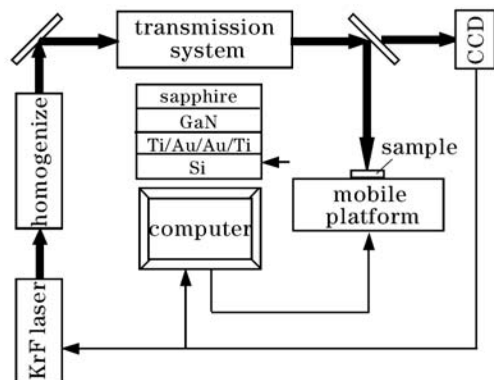

Fig. 1. Schematic diagram of laser lift-off system.

pulse laser measured by the UV sensitive CCD beam analyzer shows 10% in-spot variation and 5% pulse-to-pulse variation. By a 2-inch quertz plano-spherical lens with 110-mm focal length the laser is focused into a 1×1 (mm) spot to scan the samples fixed on the mobile platform. Before irradiating through the sapphire backside, the pulse laser is split into two beams-one for LLO and the other for real-time monitoring the quality of the laser beam. The schematic diagram of LLO system is shown in Fig. 1.

Pulse laser irradiations with energy density of 400 mJ/cm^2[17] are performed to separate GaN films from sapphire substrates. All laser irradiations are performed in air at room temperature. After irradiation the samples are heated up to 30 °C to remove sapphire substrates and then dipped in the 50% HCl solution (HCl: deionized water=1:1) to eliminate the residual metallic Ga.

Figure 2 shows the cross section SEM image of the Ga/Ti/Au/Au/Ti/Si structure. The sample appears to be free of voids at the bonding interface, indicating a uniform and complete bond of the GaN film on Si. The corresponding EDS spectra along the cross-section are shown in Fig. 3. In Au layer (at 10—12 μm), the peak intensity of Si increases sharply, indicating that Si migrates outside through Ti to Au forming the Au/Si solid solution at the interface during the bonding process. The diffusion of Au in Si is not deeply. This uniform bonding interface between GaN and Si can support the GaN layer and help GaN thin films stand more thermal stress during LLO.

AFM measurement is performed in contact mode

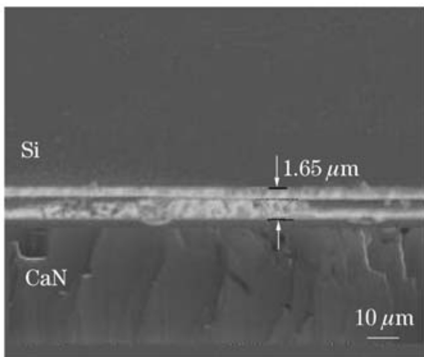

Fig. 2. Cross-section SEM image of the sample after fusion bonding and LLO.

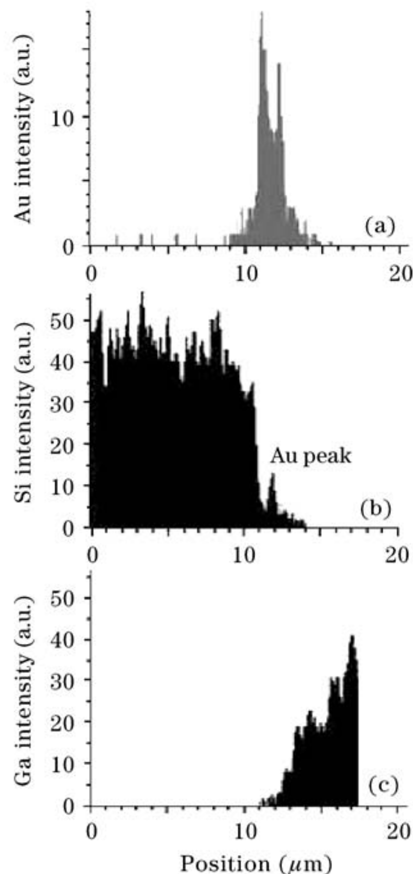

Fig. 3. EDS spectra along the cross direction of the sample after fusion bonding and LLO.

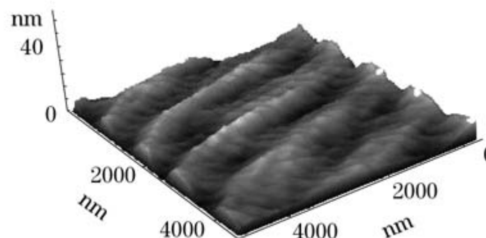

Fig. 4. AFM image of undoped GaN film after laser lift-off.

operation with a scan area of 5×5 (μm). The typical AFM image of the GaN film on Si after LLO is shown in Fig. 4. The peak to valley height is 47 nm and the root-mean-square (RMS) roughness of the GaN surface is 4.6 nm. Compared with the as-grown GaN on sapphire (about 0.3 nm), the roughness of the GaN on Si (0.32 nm)[18] is larger because of the ununiformity of GaN caused in substrate transfer. For GaN LEDs, the surface roughness of GaN can help the light generated in the active region scatter directly and improve the light extraction efficiency of the devices greatly[19]. Compared with the conventional GaN surface roughness method, LLO is more efficiency and simple. No fractures are found in GaN films after LLO, which can also verify that the uniform bonding layers are formed after low temperature bonding process.

The PL spectra of GaN films on sapphire and on Si using a continuous 325-nm He-Cd laser as an excitation

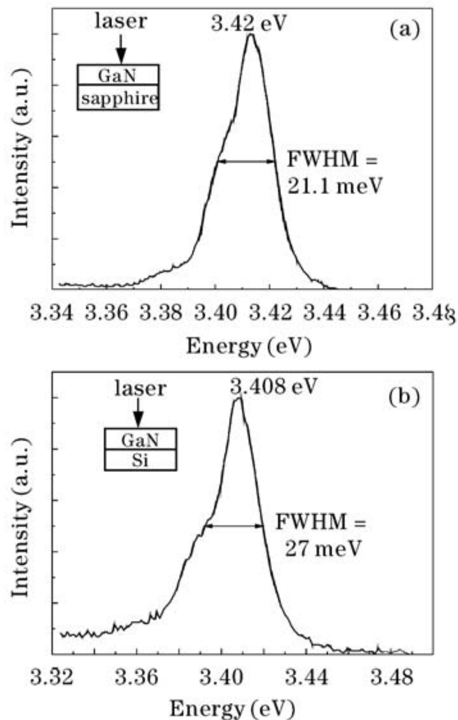

Fig. 5. PL spectra of GaN membrane before (a) and after (b) laser lift-off. Insets show the direction of He-Cd laser irradiation.

source with RPM2000 PL mapper performed at room temperature are shown in Figs. 5(a) and (b) respectively. The full-width at half maximum (FWHM) is broadened from 21.1 to 27 meV after substrate transfer, which is less than the FWHM of GaN grown directly on Si[18]. The emission peak is red shifted from 3.420 to 3.408 eV. According to Ref. [20], this red shift indicates that about 0.44-GPa biaxial stress is released after substrate transfer. The PL spectra of GaN films on sapphire and on Si at room temperature confirm that the optical quality of GaN films does not change greatly after LLO and fusion bonding technique.

In conclusion, thin GaN films are integrated with Si receptor substrates by Au/Si fusion bonding and LLO technique. The compact bonding structures GaN/Ti/Au/Au/Ti/Si come into being after pressure bonding at the temperature of 400 °C. Compared with the current wafer bonding methods, the Au/Si fusion metal bonding can simplify the fabrication process. The AFM measurement shows that the RMS roughness of surface of GaN films on Si is 4.6 nm. The emission peak of PL red shifts from 3.420 to 3.408 meV indicate about 0.44-GPa biaxial stress release. The properties of the GaN films transferred to Si receptor substrates degrade little after LLO and fusion bonding technique. The low temperature metal fusion bonding with high electrical conductivity can support the GaN film well during LLO, and plays an important role in fabricating vertical structure GaN-based LEDs.

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