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Increased thermal conductivity of free-standing low-dislocation-density GaN films

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Proposed high-power electronic and optoelectronic applications of GaN materials rely heavily on the effectiveness of heat removal from the devices. Here we report the results of our measurements of thermal conductivity in the thick free-standing GaN films prepared by hydride vapor phase epitaxy. The fabrication method allows one to grow the low-dislocation density films without the use of non-native substrates. Our experimental data show that the room temperature thermal conductivity in free-standing GaN films can be as high at 225 W/mK, which is a factor of 1.8 increase compared to a reference GaN film grown on sapphire substrate. The modeling, performed for the given sample parameters, indicates that the low-temperature thermal conductivity can reach a record value of 7460 W/mK. The presented results are important for the thermal management optimization of GaN-based devices.

1 Introduction GaN-based wide-band gap materials continue to attract significant attention as promising candidates for the next generation of microwave communication systems and optoelectronic devices [1–3]. For all envisioned applications of GaN materials, it is important to effectively remove the generated heat. Thus, the thermal conductivity K value of GaN is a very important characteristic. K varies with the crystal quality and the growth methods [4, 5]. The conventional growth methods such as metalorganic vapor phase epitaxy (MOVPE) growth of GaN films on sapphire or SiC substrates with AlN or GaN buffer layers usually result in a high threading dislocation density and stress, due to the lattice mismatch and differences in the thermal expansion coefficient between GaN and the non-native substrate. Dislocations limit the thermal conductivity [6] and electron mobility [7]. Increased thermal resistance of the structure and traps lead to degradation of the GaN-based transistor performance.

A very recently developed technique for the growth of free-standing GaN films (substrates), using the hydride vapor phase epitaxy (HVPE), allows one to fabricate GaN films with much lower threading dislocation density [8, 9]. The low dislocation densities, characteristic of HVPE-grown free-standing GaN films ($N_D \sim 10^6$ cm^{-2}), are expected to lead to higher thermal conductivity values. Indeed, it has been shown that the dislocation and point defect scattering of acoustic phonons strongly contributes to the thermal resistance of GaN films even at high temperature [6]. Here we report on the measurements of the thermal conductivity K in several free-standing thick GaN films (>230 μm) grown by HVPE. For comparison we also measure K in a conventional GaN film grown on sapphire substrate.

2 Material growth and experimental procedure

The thick GaN films were grown on (0001) sapphire substrates using horizontal type HVPE. The two-inch c-plane sapphire substrate was placed in a hot-wall HVPE reactor. Ammonia gas (NH_3) and HCl gas/Ga metal were used as N and Ga sources, respectively. Ga metal and HCl were pre-reacted to form GaCl gas, which is transported by nitrogen carrier gas to the hot growth-zone where it reacts with NH_3 at about 1000 °C to form a GaN crystal on the (0001) sapphire substrate [8, 9]. For a V–III ratio from 20 to 35, a growth rate of about 50 μm/h can be reproducibly achieved. For the preparation of free-standing GaN thick films, GaN

thick layers were removed from the sapphire substrates by the laser-assisted lift-off method. A laser beam energy density of 0.2 to 0.3 J/cm^2 was enough to release the nitrogen from the film forming a thin layer of liquid Ga. To prevent fractures induced by the wafer bowing during the laser lift-off process, the GaN/sapphire templates were kept at a temperature higher than 600 °C. The flat and smooth surfaces were obtained after mechanical polishing, which introduces subsurface damage extending up to 4000 Å below the surface. The polished growth surfaces (Ga face) were reactively ion etched to remove the damaged layer. The grown samples were inspected by X-ray diffraction and atomic force microscopy (AFM). The dislocation density is characterized by both etch pit density (EPD) and micro photoluminescence (PL) mapping.

The thermal conductivity of the thick GaN films and the reference sample was measured by the 3ω technique [10, 11]. For all the samples, a 100 nm-thick SiO_2 layer was deposited on the sample surface by plasma enhanced chemical vapor deposition (PECVD) to provide the electrical insulation required for the 3ω measurements. The thickness of the SiO_2 layer was measured by a Gaertner L116B ellipsometer on a Si reference sample that had undergone the same PECVD SiO_2 deposition process. On the surface of the samples we patterned and fabricated a 10 μm-wide Au heater-thermometer wire using the e-beam evaporation and lift-off technique. The 3ω measurements were conducted inside a vacuum cryostat in the temperature range from 80 to 400 K. A numerical program was developed to process the data and obtain K.

3 Measurements results Transmission electron microscopy (TEM) is a conventional method for determining the dislocation density in GaN crystals. However, in the case of low defect densities ($N_D < 10^7$ cm^{-2}), the TEM method becomes inaccurate due to the small measurement area [9]. To improve the accuracy, we applied EPD and micro-PL mapping analysis. Both methods gave consistent results and have shown small deviations with those obtained from TEM for $N_D \sim 10^7$ cm^{-2} [6]. Figure 1 shows a typical micro-PL mapping image for one of the examined films (sample #1, thickness $W = 287$ μm). The extracted dislocation density is $N_D \sim 3.6 \times 10^6$ cm^{-2}.

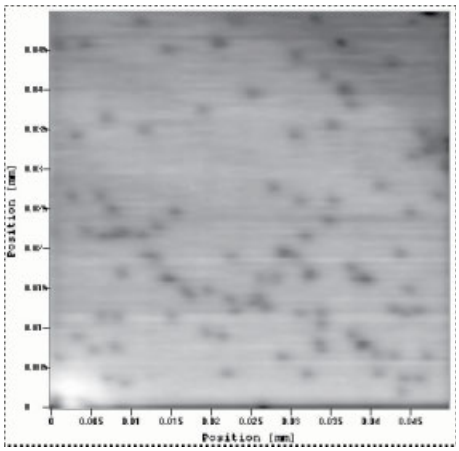

Figure 1 Micro-PL map (50 × 50 μm^2) for a free-standing GaN film. The extracted dislocation density is 3.6×10^6 cm^{-2}.

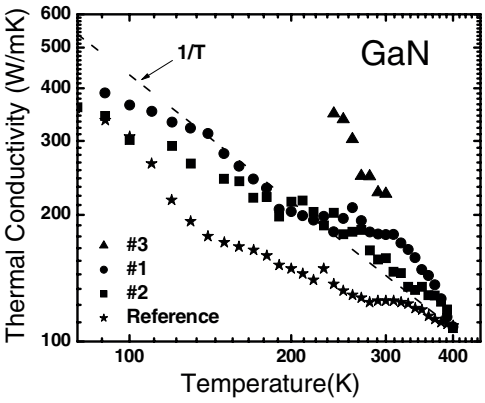

Figure 2 Measured thermal conductivity vs. temperature for three free-standing GaN films and a reference GaN/sapphire film.

The measured thermal conductivity K for three free-standing HVPE samples is plotted in Fig. 2. For comparison, we also show the measured thermal conductivity for a commercial (University Wafers) GaN film grown by HVPE on sapphire (thickness $W = 18.5$ μm). The dislocation densities for the commercial GaN/sapphire films typically vary from 10^8 to 10^{10} cm^{-2} [4]. The dislocation densities for the examined free-standing HVPE samples #1, #2 and #3, are 3.6×10^6, 6.5×10^6 and 6.2×10^6 cm^{-2}, respectively. The samples #1 and #2 are n-type with Si doping concentration $N_{Si} = 1.7 \times 10^{18}$ cm^{-3} for each sample. The sample #3 is unintentionally doped (O is major n-dopant) with the concentration $N_O = 3.0 \times 10^{16}$ cm^{-3}. One can see that the room-temperature thermal conductivity in the free-standing GaN films can be as high at 225 W/mK, which is a factor of 1.8 higher compared to the commercial GaN/sapphire reference sample. It is interesting to note that the theoretical limit for an ideal GaN crystal is $K \sim 410$ W/mK at 300 K [6].

The difference in K values decreases with increasing temperature. The latter is in line with the theory since the high-temperature thermal conductivity is limited by the three-phonon Umklapp processes. For crystalline semiconductors, the thermal conductivity follows a $1/T$ law (shown by the dashed line), which reflects the Umklapp scattering temperature dependence. Two of the free-standing GaN films manifest a similar trend. In the commercial GaN/sapphire sample, $K \sim T^{-0.5}$. Based on theoretical considerations, Zou et al. [6] attributed such dependence to a large defect concentration and, correspondingly strong phonon scattering on point defects. The fact that in the sample with low dislocation density, the thermal conductivity is sensitive to the presence of dopants even at rather high temperature (200–300 K) also agrees with Refs. [4–6]. Thermal conductivity is larger in the undoped sample due to the reduced phonon scattering on point defects. The size effects (phonon–boundary scattering) may also play a role in thin films, particularly at low temperature. Our experimental

results are in line with the measurements reported for the lateral epitaxial overgrown GaN samples studied in Refs. [4, 5].

Using the calculation procedure for GaN thermal conductivity previously developed by some of us [11] we estimated the low-temperature thermal conductivity in the free-standing HVPE GaN films. For the typical material parameters of the HVPE samples, the low-temperature peak K value can be as high as 7460 W/mK.

4 Conclusions We measured the thermal conductivity K of free-standing low-dislocation density GaN films prepared by the HVPE method. The measurements were performed using the 3ω techniques in a temperature range from 80 to 400 K. Our results show that the typical room-temperature thermal conductivity values in the free-standing GaN films are much higher than in the conventional GaN films grown on non-native substrates. Due to the high quality of the HVPE free-standing samples, K can be as high as 225 W/mK at T = 300 K. Further improvements in the free-standing GaN fabrication may help to overcome the thermal management issues in GaN technology.

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