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Temperature dependence of thermal conductivity of $Al_xGa_{1-x}N$ thin films measured by the differential 3ω technique

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Reliable values of thermal conductivity of thin films made of GaN and its alloys are important for further development of nitride technology due to the problem of self-heating in GaN-based power transistors and optical devices. Using the differential 3ω technique we measured the thermal conductivity of $Al_xGa_{1-x}N$ thin films ($x=0$ and 0.4) grown by the hydride vapor phase epitaxy. Thermal conductivity of the examined $Al_{0.4}Ga_{0.6}N$ alloy, which is about 25 W/mK at 300 K, displays a rather unusual temperature dependence. A noticeable growth of the thermal conductivity with temperature up to 350 K is more characteristic for amorphous or completely disordered materials. The measured high-temperature thermal conductivity data are in good agreement with predictions based on the virtual crystal model. Obtained results are important for modeling the self-heating effects in GaN transistors and can be used for the device structure optimization. *© 2004 American Institute of Physics*. [DOI: 10.1063/1.1829168]

Self-heating presents a serious problem for continuing development of GaN-based technology, specifically for high-power high-frequency transistors and optoelectronic devices.[1–3] It has been reported that self-heating effects in GaN transistors can seriously degrade the device performance and induce problems such as drain current reduction, thermal breakdown, and, possibly, current gain dispersion or collapse. Solving the self-heating problem is therefore becoming an urgent task for the researchers in the field. Self-heating involves two stages, i.e., the heat generation and heat dissipation processes. The former is determined by the input power level and the latter depends uniquely on the thermal transport properties of the materials used in the device structure.

In this letter we report results of the investigation of the thermal conductivity K of $Al_xGa_{1-x}N$ thin films ($x=0$ and 0.4) grown by the hydride vapor phase epitaxy (HVPE). The accurate values of thermal conductivity in $Al_xGa_{1-x}N$ films with high Al content are important for evaluation and modeling of the performance of AlGaN/GaN heterostructure field-effect transistors (HFETs). High Al-content layers are currently used for increasing the polarization field and the piezoelectric charge density in AlGaN/GaN HFETs and for tuning the wavelength of the emitted light in optoelectronic devices. They were also proposed for reducing flicker noise level in AlGaN/GaN HFETs.[4] A study of the variation of the thermal conductivity of $Al_xGa_{1-x}N$ alloys with the Al content x has not been carried out yet.

There is significant discrepancy in the reported values for the thermal conductivity of GaN bulk material and thin films. Sichel and Pankove[5] showed that K of bulk GaN decreases as $k \sim T^{-0.76}$ in the range from 200 to 360 K. The room temperature value obtained by them was 130 W/mK. Results of Slack *et al.*[6] reveal that K decreases with temperature as $k \sim T^{-1.22}$ from 40 to 300 K while the room temperature value was 200 W/mK. There are limited data on thermal conduction in GaN thin films.[7–9] The reported room-temperature K values measured for lateral epitaxial overgrown GaN thin films were 155 W/mK[7] and 185–205 W/mK,[8] respectively. Using scanning thermal microscopy technique, Florescu *et al.*[8] established that thermal conductivity of GaN films depends on the concentration of defects and impurities even at room temperature. Explanation and quantitative analysis of this dependence was given by Kotchetkov *et al.*[10] From the optical pump-and-probe measurements Daly *et al.*[9] established K values of the molecular beam epitaxy (MBE) grown polycrystalline GaN films and metalorganic chemical vapor deposition (MOCVD) grown $Al_xGa_{1-x}N$ films in the temperature range from 150 to 400 K. The reported data indicate that the thermal conductivity of the measured films was almost an order of magnitude lower than that of bulk GaN samples and had little temperature dependence around 300 K.[9]

We have experimentally investigated the thermal conductivity of GaN and $Al_{0.4}Ga_{0.6}N$ films adopting the differential 3ω technique developed by Cahill[11] for thin films. The experimental results were compared with the predictions of the phonon-hopping[12] and virtual crystal models.[13] The investigated samples were 18.5-μm-thick GaN film and 0.7-μm-thick $Al_{0.4}Ga_{0.6}N$ film. The samples were grown on c-plane sapphire substrate by the modified HVPE technology.[14] We have verified the Al mass fraction of the alloy films using x-ray diffraction. Since the GaN samples were not semi-insulating we deposited a 93-nm-thick SiO_2 layer on the sample surface by plasma enhanced chemical vapor deposition (PECVD) to provide electrical insulation required for the 3ω measurements. A Si reference sample, similarly coated with PECVD SiO_2 layer, was prepared for analysis (subtraction) of the data obtained in the differential 3ω technique. The thickness of the SiO_2 layer was measured by the Gaertner L116B Ellipsometer. The $Al_{0.4}Ga_{0.6}N$ sample was semi-insulating so that no additional insulation layer was required. On the surface of all samples we patterned and fabricated the gold 5-μm-wide heater-thermometer wire using e-beam evaporation and lift-off technique. The 3ω mea-

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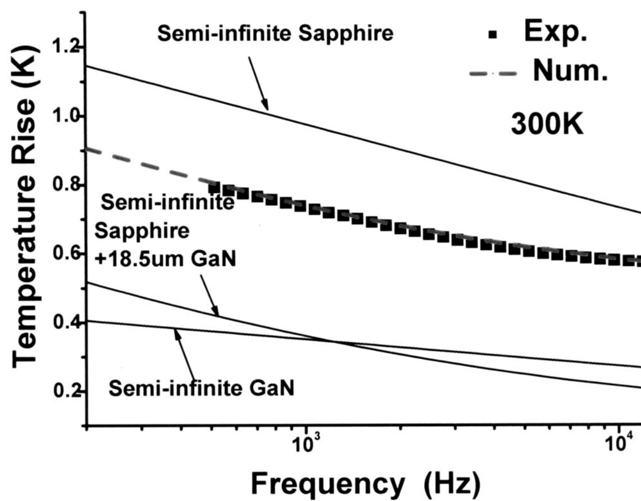

FIG. 1. Temperature rise as a function of frequency at 300 K in GaN thin film. The squares correspond to measured data while the dashed line is obtained from the numerical fitting with the thermal conductivity values of SiO_2, GaN, and sapphire to be 1.292, 125, and 29 W/mK, respectively. For comparison, the straight lines indicate the simulation results of the temperature rise under the assumption that the sample is semi-infinite sapphire bulk, semi-infinite GaN bulk, or 18.5-μm-thick GaN film on semi-infinite sapphire bulk.

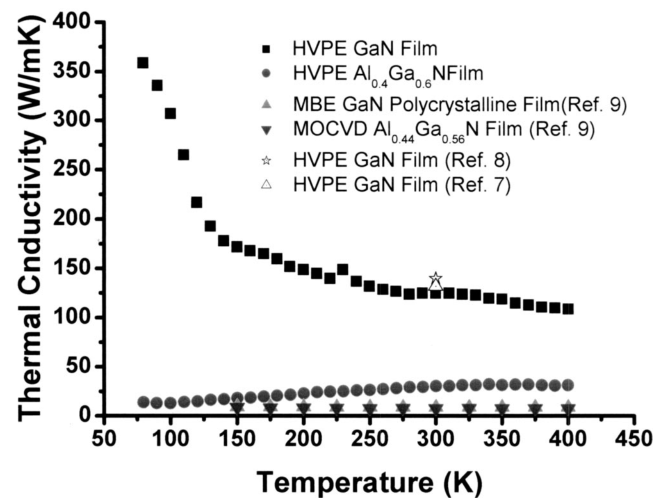

FIG. 2. Thermal conductivity K of GaN and $Al_{0.4}Ga_{0.6}N$ thin films in the temperature range from 80 to 400 K. Note an unusually strong increase of K with temperature in $Al_{0.4}Ga_{0.6}N$ alloy up to the temperature of 350 K. For comparison, data points reported for similar material systems are also shown.

surements were conducted inside a vacuum cryostat in the temperature range from 80 to 400 K.

Unlike Lou *et al.*,[7] who used the slope method in analysis of the 3ω data, we adopted the differential subtraction to obtain the thermal conductivities of both the substrate and films. To extract the thermal conductivity data we used a numerical program based on the analytical solution of the 3ω heat conduction model to fit the experimental data.[15] The advantage of this method is that the thermal wavelength induced slope bending and in-plane heat spreading effects, which may introduce error in slope method, are accommodated in the solution. Figure 1 shows typical experimental data with the calculated curves for data fitting. The frequency-dependent temperature rise measured for SiO_2 (93 nm)+GaN (18.5 μm)+sapphire (substrate) sample is shown by the squares. The dashed line is calculated from the numerical program with the corresponding bulk thermal conductivity values for each layer of the material. The thermal conductivity of SiO_2 film is obtained from the Si reference sample measurements. Three straight lines are calculated under the assumption that the material composition of the sample is: (i) semi-infinite sapphire substrate only, (ii) semi-infinite GaN bulk only, and (iii) 18.5-μm-thick layer of GaN on bulk sapphire. It can be seen from these plots that as the frequency increases (thermal wavelength shortens) the slope of the measured temperature rise versus frequency changes from that of the semi-infinite sapphire to that of the semi-infinite GaN.

The measured thermal conductivities of GaN and $Al_{0.4}Ga_{0.6}N$ films are shown in Fig. 2. For comparison, we also show the reported room temperature K values for GaN films from Refs. 7 and 8 and the temperature-dependent K values for MBE-grown polycrystalline GaN and MOCVD-grown $Al_{0.44}Ga_{0.56}N$ films from Ref. 9. The measured room temperature thermal conductivity of the examined HVPE-grown GaN film is 125 W/mK. This value, although smaller, is close to the values reported by both Lou *et al.*[7] and Florescu *et al.*,[8] and is smaller than the bulk value reported by Slack *et al.*[6] The measured temperature dependence of the thermal conductivity in GaN film is typical of that of bulk crystal. The latter suggests that the bulk scattering terms, i.e., Umklapp and point-defect scattering, are major phonon relaxation mechanisms in the sample. Somewhat reduced thermal conductivity value and smaller slope of the $K-T$ curve can be an indication of the strong defect and boundary scattering.

One can see from Fig. 2 that the thermal conductivity of the $Al_{0.4}Ga_{0.6}N$ film is much smaller than that of GaN film but larger than that of MOCVD grown polycrystalline $Al_{0.44}Ga_{0.56}N$ film investigated by Daly *et al.*[9] A somewhat unusual feature observed in our measurements was that the thermal conductivity of the $Al_{0.4}Ga_{0.6}N$ film increased noticeably with temperature up to $T=350$ K. This type of temperature dependence is normally observed in amorphous or completely disordered systems. It is though in line with the calculations of thermal conductivity of polycrystalline AlGaN films[16] based on the phonon-hopping model.[12] Phonon-boundary scattering in the 0.7-μm-thick film may also contribute to the overall reduction of the thermal conductivity in the $Al_{0.4}Ga_{0.6}N$ film, particularly at low temperature.

As it was outlined, a systematic study of the variation of thermal conductivity of the $Al_xGa_{1-x}N$ alloy with the Al content x is of significant practical importance for AlGaN/GaN HFET performance enhancement. Virtual crystal model[13] has been proven to be an effective theoretical tool for simulation of the thermal conductivity of alloy systems, such as Si_xGe_{1-x} and $Al_xGa_{1-x}As$,[13,17] especially at high temperature. Using the same approach, we recast the virtual crystal model for $Al_xGa_{1-x}N$ alloy system. The details of the calculations are reported elsewhere.[18] For model validation, we compared the simulated $K-T$ curves with the measured values ($x=0.0$ and 0.4) at 200, 300, and 400 K. The results are presented in Fig. 3. For all examined points the measured values are in good agreement with the theoretical predictions. Some discrepancies at 200 K can be explained by the stronger size effect at low temperature, which are underestimated in the model.

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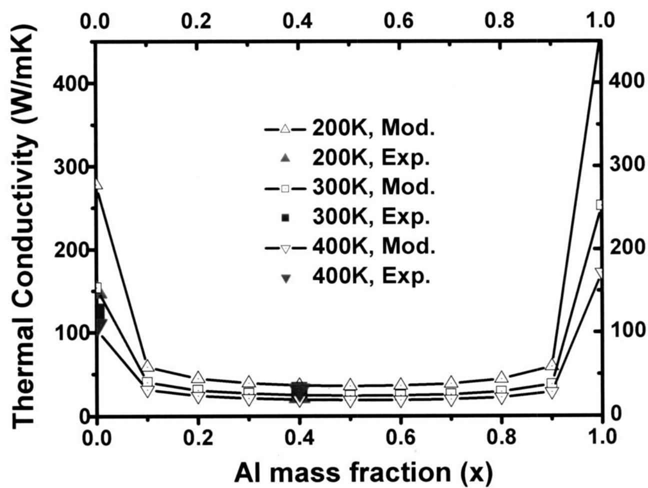

FIG. 3. Thermal conductivity as a function of Al mass fraction x for $Al_xGa_{1-x}N$ alloy system. The theoretical curves are calculated from the virtual crystal model, the points indicate the measured data.

In summary, we measured the temperature dependence of the thermal conductivity of GaN and $Al_{0.4}Ga_{0.6}N$ films using the differential 3ω technique. Thermal conductivity of the examined $Al_{0.4}Ga_{0.6}N$ alloy, which is about 25 W/mK at 300 K, grows with temperature up to 350 K. The latter is characteristic for completely disordered materials. The measured high-temperature thermal conductivity data are in good agreement with the theoretical curves calculated using the virtual crystal and phonon-hopping models. Obtained results are important for further development of nitride technology.

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[1] R. Gaska, Q. Chen, J. Yang, A. Osinsky, M. A. Khan, and M. S. Shur, IEEE Electron Device Lett. **18**, 492 (1997).
[2] K. Fillipov and A. A. Balandin, MRS Internet J. Nitride Semicond. Res. **8**, 4 (2003).
[3] V. O. Turin and A. A. Balandin, Electron. Lett. **40**, 81 (2004).
[4] A. A. Balandin, S. Morozov, G. Wijeratne, S. J. Cai, R. Li, J. Li, K. L. Wang, C. R. Viswanathan, and Y. Dubrovskii, Appl. Phys. Lett. **75**, 2064 (1999).
[5] E. K. Sichel and J. I. Pankove, J. Phys. Chem. Solids **38**, 330 (1977).
[6] G. A. Slack, L. J. Schowalter, D. Morelli, and J. A. Freitas, Jr., J. Cryst. Growth **246**, 287 (2002).
[7] C.-Y. Lou, H. Marchand, D. R. Clarke, and S. P. DenBaars, Appl. Phys. Lett. **75**, 4151 (1999).
[8] D. I. Florescu, V. M. Asnin, F. H. Pollak, A. M. Jones, J. C. Ramer, M. J. Schurman, and I. Ferguson, Appl. Phys. Lett. **77**, 1464 (2000).
[9] B. C. Daly, H. J. Maris, A. V. Nurmikko, M. Kuball, and J. Han, J. Appl. Phys. **92**, 3820 (2002).
[10] D. Kotchetkov, J. Zou, A. A. Balandin, D. I. Florescu, and F. H. Pollak, Appl. Phys. Lett. **79**, 4319 (2001); J. Zou, D. Kotchetkov, A. A. Balandin, D. I. Florescu, and F. H. Pollak, J. Appl. Phys. **92**, 2534 (2002).
[11] D. G. Cahill, Rev. Sci. Instrum. **61**, 802 (1990).
[12] L. Braginsky, N. Lukzen, V. Shklover, and H. Hofmann, Phys. Rev. B **66**, 134203 (2002).
[13] B. Abeles, Phys. Rev. **131**, 1906 (1963).
[14] B. Lam, G. H. Gainer, S. Bidnyk, A. Elgawadi, G. H. Park, J. Krasinski, J. J. Song, D. V. Tsvetkov, and V. A. Dmitriev, Mater. Res. Soc. Symp. Proc. **639**, G6.4.1 (2001).
[15] W. L. Liu, T. Borca-Tasciuc, G. Chen, J. L. Liu, and K. L. Wang, J. Nanosci. Nanotechnol. **1**, 39 (2001).
[16] D. Kotchetkov and A. A. Balandin, Mater. Res. Soc. Symp. Proc. **764**, 215 (2003).
[17] M. A. Afromowitz, J. Appl. Phys. **44**, 1292 (1973).
[18] W. L. Liu and A. A. Balandin (unpublished).

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