Anisotropic thermal conductivity of AlGaN/GaN superlattices

A Filatova-Zalewska¹, Z Litwicki¹, K Moszak¹,², W Olszewski²,³, K Opolszyńska²,³, D Pucicki²,⁴, J Serafińczuk²,⁴, D Hommel²,³ and A Jeżowski¹

¹ Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Okólna 2, 50-422 Wrocław, Poland
² Łukasiewicz Research Network—PORT Polish Center for Technology Development, Siałłowicka 147, 54-066 Wrocław, Poland
³ Faculty of Physics, University of Wrocław, Plac Maxa Borna 9, 50-204 Wrocław, Poland
⁴ Faculty of Microsystem Electronics and Photonics, Wrocław University of Science and Technology, Janiszewskiego 11/17, 50-372 Wrocław, Poland

E-mail: a.filatova@intibs.pl

Received 15 July 2020, revised 1 October 2020
Accepted for publication 29 October 2020
Published 26 November 2020

Abstract

High thermal conductivity is an important parameter for nitride-based power electronic and deep-UV light emitters. Especially in the latter case short period superlattices and multicomponent alloys are used and the knowledge of the thermal properties of the binary compounds is sufficient. In-plane and cross-plane thermal conductivity of AlGaN/GaN superlattices were measured by differential two-wire \(3\omega\) method in the temperature range from 147 to 325 K. Samples were grown by metalorganic vapor phase epitaxy; the structure quality and accuracy of superlattice structures preparation were verified by means of HRXRD and transmission electron microscopy. It was observed, that value of thermal conductivities decrease with decreasing period thickness, while temperature dependencies differ from each other—in-plane thermal conductivity decreases, and cross-plane—increases with increasing temperature. Callaway method was used for thermal conductivity calculation; dependence of boundary scattering rate on the phonon wavelength was taken into account. Minimum thermal conductivity was added to calculated values to include the influence of high frequency acoustic phonons and optical phonons on the heat transport. Calculations are in good agreement with experimental results.

Keywords: thermal conductivity, superlattice, \(3\omega\) method, metalorganic vapor phase epitaxy, callaway method, phonon scattering

(Some figures may appear in colour only in the online journal)

1. Introduction

Nowadays, AlN, GaN and GaN-based alloys and heterostructures have a wide variety of applications: ultraviolet detectors [1, 2], light-emitting diodes [3, 4], high-electron mobility transistors [5, 6], solar cells [7, 8], thermoelectric materials [9, 10]. Weak heat dissipation is a serious problem of GaN-based devices—it substantially decreases the efficiency of high-electron mobility transistors. High thermal conductivity could lead to a better performance of such devices. On the other hand, good thermoelectric material must have small thermal conductivity, high Seebeck coefficient and high electrical conductivity [11]. In any case, the thermal conductivity of the material used in the device plays an important role and has to be known.
Even though the thermal conductivity of bulk and film GaN was extensively investigated over the last decades [12–18], there were only several reports on thermal conductivity of AlGaN films and AlN/GaN superlattices. Results of the measurements of Al$_x$Ga$_{1-x}$N films (with $x$ changing from 0.1 to 0.44) showed that thermal conductivity decreases with increasing amount of Al mass fraction and decreasing film thickness [19–24]. Both increase [21, 24] and decrease [19] of thermal conductivity with increasing temperature was observed.

An extensive research on cross-plane thermal conductivity of (x AlN/y GaN)$_n$ (x $\approx$ 4 nm, 2 nm $< y < 100$ nm, 5 $< n <$ 30) superlattices was published in 2009 [25]. Time-domain thermoreflectance was used for measurement in the temperature range from 90 to 600 K. Thermal conductivity decreased with decreasing temperature and decreasing thickness of GaN layer. Authors tried to explain thermal conductivity period thickness and temperature dependence by attributing additional thermal resistance in the superlattice to the thermal resistance of the interfaces, by considering possible greater influence of optical phonons to heat transfer or formation of phonon minibands, but none of those considerations adequately explained experimental results. Calculations using Debye–Callaway model with the assumption of phonon-wavelength dependent boundary scattering rate provided an opportunity to conclude, that long-wavelength phonons are the dominant heat carriers in short period superlattices, and scattering of long-wavelength phonons at AlN/GaN interfaces has a strong dependence on phonon wavelength.

The aim of the present study is the investigation of temperature and period thickness dependence of anisotropic thermal conductivity of AlGaN/GaN superlattices. To achieve this goal, differential two-wire 3$\omega$ method was used for thermal conductivity measurement, while for its calculation Callaway method with the assumption of phonon-wavelength dependent boundary scattering rate was implemented.

2. Experimental details

2.1. Sample preparation

All investigated structures were grown on two-inch diameter, 430 $\mu$m thick, (0001)-oriented sapphire using metalorganic vapor phase epitaxy. Hydrogen (H$_2$) was used as a carrier gas and ammonia (NH$_3$), trimethylgallium (TMGa), trimethylaluminium (TMAI) as precursors. A 1.6 $\mu$m thick undoped GaN buffer layer was grown at 1060 °C, followed by the growth of superlattice at 1080 °C. Five samples with superlattices were prepared. Schematic illustration of investigated samples is shown in the figure 1, while properties of the superlattices are summarized in the table 1. On the epitaxial structures, a SiO$_2$ layer was deposited by plasma-enhanced vapor deposition. Afterwards, on the structures with fabricated dielectric layers, Au heaters were evaporated and shaped using optical lithography technique.

x-ray diffraction technique (XRD) was used to determine structural data of each investigated sample. Thickness of subsequently repeated AlGaN and GaN layers, as well as the Al percentage, were determined by means of XRD curves fitting. The quality of the epitaxial samples, including interfaces sharpness and uniformity were verified by transmission electron microscopy (TEM) imagining (is shown in the figure 2).

2.2. Thermal conductivity measurement

The 3$\omega$ method is used for the thermal conductivity measurement of films and bulk materials [26]. Deposited on the sample thin golden wire functions both as a heater and thermometer. Driven along the heater alternate current causes heat generation of frequency 2$\omega$ and temperature rise in the sample. The measured third harmonic component of the voltage drop along the wire V$_{3\omega}$ is used for the determination of the temperature rise of the heater, and then the thermal conductivity of the specimen is calculated.

The differential two-wire 3$\omega$ method was used for the measurement of the in-plane and cross-plane thermal conductivities of the AlGaN/GaN superlattices. Earlier it was successfully used for the investigation of anisotropic thermal conductivity of Si/Ge and Ge quantum-dot superlattices [27–30]. For five investigated samples a reference sample, consisted of the sapphire substrate and 1.6 $\mu$m thick GaN buffer layer, was prepared (will be referred to as sample ‘A’). A sapphire sample (‘B’) was used as the reference to ‘A’. A SiO$_2$ layer was deposited on all samples, and on the top of dielectric layer two golden 3$\omega$ wires (with widths of $\approx$3 $\mu$m
and 20 μm) were deposited; width of every heater was measured with scanning electron microscopy. Firstly, measurements on both wires were conducted for the reference sample. Then they were used for determination of errors. Secondly, the same procedure was implemented for estimation of the in-plane and cross-plane thermal conductivities from the sample with investigated superlattice and sample ‘A’.

Measurements were carried out in the temperature range from 147 to 325 K (choice of the temperature range was dictated by the properties of the investigated superlattices). In accordance to this model, thermal conductivity can be written in the following form

\[
 k = \frac{k_B}{2\pi^2\nu} \left( \frac{k_B}{\hbar} \right)^3 \tau_C \left[ \int_0^{\theta_D/T} \frac{\tau_C}{\tau_N} x^4 e^x \left( e^x - 1 \right) dx \right. \\
 + \left. \int_0^{\theta_D/T} \frac{\tau_C}{\tau_R} x^4 e^x \left( e^x - 1 \right) dx \right]^{-1} 
\]

where \( k_B \) is the Boltzmann constant, \( h \) is the reduced Planck constant, \( \nu \) is the phonon group velocity, \( \theta_D \) is Debye temperature, \( x = \hbar \omega / (k_B T) \), \( \omega \) is frequency. The total scattering rate can be expressed as

\[
 \tau_C = \frac{1}{\tau_N} + \frac{1}{\tau_R} 
\]

where \( \tau_N^{-1} \) corresponds to relaxation rate in Normal processes, and \( \tau_R^{-1} \)—in resistive processes. The former can be written as

\[
 \tau_N^{-1} = N \omega^2 T^3, 
\]

3. Calculation

The cross-plane thermal conductivity of superlattice was calculated by [32]

\[
 k_{cross} = \frac{L_{AlGaN} + L_{GaN}}{2} \left( \frac{L_{AlGaN}}{k_{AlGaN} c_{AlGaN}^i} + \frac{L_{GaN}}{k_{GaN} c_{GaN}^i} + 2 \right)^{-1} 
\]

while for the in-plane thermal conductivity computation the following equation was used [32, 33]:

\[
 k_{in} = \frac{L_{AlGaN} k_{AlGaN} + L_{GaN} k_{GaN}^i}{L_{AlGaN} + L_{GaN}}, 
\]

where \( L_{AlGaN} \) and \( L_{GaN} \) are the thicknesses of the AlGaN and GaN layers of superlattice, \( L_{AlGaN} + L_{GaN} \) is the period thickness, \( k_{AlGaN} \) and \( k_{GaN} \) are thermal conductivities of AlGaN and GaN layers, symbols \( c \) and \( i \) correspond to the cross-plane and in-plane directions, \( G \) is the thermal boundary conductance.

For calculation of thermal conductivities of AlGaN and GaN layers the Callaway model was used [34]. In accordance to this model, thermal conductivity can be written in the following form

\[
 k = \frac{k_B}{2\pi^2\nu} \left( \frac{k_B}{\hbar} \right)^3 \tau_C \left[ \int_0^{\theta_D/T} \frac{\tau_C}{\tau_N} x^4 e^x \left( e^x - 1 \right) dx \right. \\
 + \left. \int_0^{\theta_D/T} \frac{\tau_C}{\tau_R} x^4 e^x \left( e^x - 1 \right) dx \right]^{-1} 
\]

3. Calculation

The cross-plane thermal conductivity of superlattice was calculated by [32]

\[
 k_{cross} = \frac{L_{AlGaN} + L_{GaN}}{2} \left( \frac{L_{AlGaN}}{k_{AlGaN} c_{AlGaN}^i} + \frac{L_{GaN}}{k_{GaN} c_{GaN}^i} + 2 \right)^{-1} 
\]

while for the in-plane thermal conductivity computation the following equation was used [32, 33]:

\[
 k_{in} = \frac{L_{AlGaN} k_{AlGaN} + L_{GaN} k_{GaN}^i}{L_{AlGaN} + L_{GaN}}, 
\]

where \( L_{AlGaN} \) and \( L_{GaN} \) are the thicknesses of the AlGaN and GaN layers of superlattice, \( L_{AlGaN} + L_{GaN} \) is the period thickness, \( k_{AlGaN} \) and \( k_{GaN} \) are thermal conductivities of AlGaN and GaN layers, symbols \( c \) and \( i \) correspond to the cross-plane and in-plane directions, \( G \) is the thermal boundary conductance.

For calculation of thermal conductivities of AlGaN and GaN layers the Callaway model was used [34]. In accordance to this model, thermal conductivity can be written in the following form

\[
 k = \frac{k_B}{2\pi^2\nu} \left( \frac{k_B}{\hbar} \right)^3 \tau_C \left[ \int_0^{\theta_D/T} \frac{\tau_C}{\tau_N} x^4 e^x \left( e^x - 1 \right) dx \right. \\
 + \left. \int_0^{\theta_D/T} \frac{\tau_C}{\tau_R} x^4 e^x \left( e^x - 1 \right) dx \right]^{-1} 
\]

where \( k_B \) is the Boltzmann constant, \( h \) is the reduced Planck constant, \( \nu \) is the phonon group velocity, \( \theta_D \) is Debye temperature, \( x = \hbar \omega / (k_B T) \), \( \omega \) is frequency. The total scattering rate can be expressed as

\[
 \tau_C^{-1} = \frac{1}{\tau_N} + \frac{1}{\tau_R} 
\]

where \( \tau_N^{-1} \) corresponds to relaxation rate in Normal processes, and \( \tau_R^{-1} \)—in resistive processes. The former can be written as

\[
 \tau_N^{-1} = N \omega^2 T^3, 
\]
while the latter
\[ \tau_R^{-1} = \tau_B^{-1} + \tau_{PD}^{-1} + \tau_U^{-1} = \frac{\nu}{d} + A\omega^4 + B\omega^2T \exp\left(\frac{-\theta}{3T}\right), \]  
(6)

where \( \tau_B, \tau_{PD} \) and \( \tau_U \) denote relaxation times for boundary scattering, point-defect (impurities and alloy component) scattering and Umklapp scattering, respectively, \( d \) is the boundary scattering length. Appropriate determination of the latter plays crucial role in thermal conductivity estimation.

Assuming, that interfaces are more efficient at scattering of short-wavelength phonons and transmission of long-wavelength phonons, one has to take into account dependence of boundary scattering rate on the phonon wavelength [25, 35]. We follow work [25] in definition of a boundary scattering length

\[ d = \frac{l}{1 - p}, \]  
(7)

where \( l \) is the characteristic length and \( p \) is the specularity parameter (the fraction of incident phonons that are specularly scattered at the interfaces), which can be expressed as [32, 35, 36]

\[ p = \exp(-4\eta^2k_p^2), \]  
(8)

where \( \eta \) is the rms length of the interface roughness and \( k_p \) is the phonon wavevector. Finally, phonon-boundary scattering rate is given by

\[ \tau_R^{-1} = \frac{\nu}{l}(1 - \exp(-4\eta^2k_p^2)). \]  
(9)

Debye temperature and phonon group velocity of AlGaN alloy were evaluated from the one of GaN and AlN with the virtual crystal model [37]. Parameters \( N, A \) and \( B \) from equations (5) and (6) used in calculations, are given in the table 2; same values of those parameters were used for computation of both the in-plane and cross-plane thermal conductivities. Parameter \( l \) in equation (9) was equal to layer thickness for the cross-plane thermal conductivity calculation. For the in-plane thermal conductivity the characteristic length was chosen to give best fit to the measured conductivity, and was three times the layer thickness. The rms length of the interface roughness was used as a fitting parameter.

Since Callaway model does not include heat transport by high frequency acoustic phonons and optical phonons, we followed approach from the work [25], and determined thermal conductivity of these phonons by calculating minimal thermal conductivities [38] of AlGaN and GaN. We estimate, that in the investigated temperature range, contribution of these phonons to thermal conductivity changes from 3% at 147 K to about 10% at 325 K. Finally, in-plane or cross-plane thermal conductivity of AlGaN or GaN layer was equal to the sum of: the thermal conductivity, calculated with Callaway model, and minimum thermal conductivity.

For calculation of thermal boundary conductance diffuse mismatch model (DMM) and acoustic mismatch model (AMM) were used [33]. In the AMM [39, 40] phonons are treated as plane waves propagating through a continuum media. No scattering phenomenon occurs at the interface, phonon can be reflected or transmitted through the specular interface; probability of phonon transmission through the plane interface depends on phonon frequency and difference in the density and sound velocity between two media. On the other hand, DMM [40] postulates that all phonons are scattered randomly on the interface, losing memory of their direction, polarization and material of the origin, keeping only their frequency constant. After such scattering, the probability for a phonon to propagate into material is proportional to materials density of states.

As it was mentioned at the beginning of the section, the Callaway model was used for the determination of thermal conductivity of AlGaN and GaN layers. One has to keep in mind some disadvantages of application of this method for the superlattice thermal conductivity modelling. First of all, the Callaway model is based on the Debye approximation, i.e. the phonon dispersion relation is assumed to be linear. It could be necessary to use full dispersion relation for the accurate determination of thermal conductivity. Second, under the relaxation time approximation, the total scattering rate of the phonon is assumed to be the sum of the relaxation rates in normal and resistive processes. The latter includes point-defect, Umklapp and boundary scattering processes. While investigating thermal conductivity of superlattices, one could expect that the phonon-boundary scattering process would have more complex form, than the one, given with equation (9). An interplay between point-defect and Umklapp and phonon scattering on the rough interface between the layers has to be taken into account [41].

In order to get over those lacks, one can model thermal conductivity of superlattices using molecular dynamics [42, 43], Green’s function [44] or Boltzmann transport equation [32, 45, 46]. But despite mentioned disadvantages, Callaway model still can provide a rather good estimation of thermal conductivity [25, 47, 48].

| Number of periods | A [s K⁻⁴] | B [s K⁻¹] | N [s K⁻³] |
|-------------------|-----------|-----------|-----------|
| 9, 18, 27, 36, 72 | GaN       | 1.35 · 10⁻⁴⁵ | 2.54 · 10⁻¹⁹ | 2.11 · 10⁻²³ |
| 9, 36             | Al₀₂₅Ga₀₇₅N | 2.67 · 10⁻⁴⁶ | 1.71 · 10⁻¹⁹ | 1.39 · 10⁻²³ |
| 18                | Al₀₂₂₅Ga₀₇₅N | 2.28 · 10⁻⁴³ | 1.84 · 10⁻¹⁹ | 1.50 · 10⁻²³ |
| 27                | Al₀₂₃₇₅Ga₀₇₅N | 2.39 · 10⁻⁴³ | 1.8₁ · 10⁻¹⁹ | 1.47 · 10⁻²³ |
| 72                | Al₀₂₂₅Ga₀₇₅N | 2.46 · 10⁻⁴³ | 1.7₈ · 10⁻¹⁹ | 1.₄₅ · 10⁻²³ |
4. Results and discussion

In figure 3 are shown measured cross-plane and in-plane thermal conductivities of superlattices. One can see, that both thermal conductivities decrease with decreasing period thickness, and this reduction can be attributed to the increased role of the phonon scattering on the interfaces of superlattice. Cross-plane thermal conductivity increases with increasing temperature, while for the in-plane thermal conductivity the opposite temperature dependence is observed. Similar temperature dependence of anisotropic thermal conductivity was observed in works [29, 49] for Si/Ge superlattices. Scattering of phonons on the interfaces can describe the cross-plane thermal conductivity temperature dependence, while for the in-plane thermal conductivity increasing with increasing temperature influence of the normal three-phonon scattering on thermal conductivity can be responsible for such thermal conductivity trend [49].

Thermal conductivity of investigated superlattices was calculated using approach, presented in the previous section. As it was mentioned, parameters N, B and A, used for calculation of scattering rate in normal, Umklapp and point-defect scattering processes were the same for both the in-plane and cross-plane thermal conductivities. Only the interface scattering differed both thermal conductivities.

In figure 3 calculated thermal conductivities for different interface roughness values are shown. One can see, that for the in-plane thermal conductivity a good agreement between experimental and calculation results is obtained. This agreement suggests, that for examined superlattices, as for AlN/GaN superlattices, investigated in work [25], short-wavelength phonons scatter at the interface between two materials, while long-wavelength phonons transmit through it, making them the dominant heat carriers. Following Ziman [35] in definition of short and long wavelength phonons, one should consider the latter as the phonons with values of wavelength, much exceeding the rms length of the roughness, so parameter p is near unity. For the short-wavelength phonons parameter p is small, and in our case we assume that the wavelengths of those phonons will not exceed 1.5 nm. For 44.6 nm period superlattice optimal-fit rms roughness is 0.15 nm, and its value decreases with decreasing superlattice period, reaching the value of 0.05 nm for 4.8 nm period superlattice. This reduction of roughness value can indicate improvement of interface quality with decreasing superlattice period thickness. Moreover, such small values of the roughness evidence a high-quality of the interfaces.

For each sample, three approaches were used for the cross-plane thermal conductivity evaluation. It was calculated with equation (1), and thermal boundary conductance was determined with the use of AMM, DMM, or disregarded. The interface roughness was equal to the optimal fit value from the in-plane conductivity calculations. Calculation of thermal conductivity with neglected thermal boundary conductance results in its overestimation, while taking into account boundary conductance leads to underestimation of
conductivity. Increase in the rms length of surface roughness, used in calculations of anisotropic thermal conductivity, did not lead to significant improvement of agreement between experimental and calculation results. This means, that the apparent thermal boundary conductance is higher, than the one, which is calculated with AMM or DMM model.

In figure 4 dependence of thermal conductivity on period thickness is shown at 300 K (a) and 200 K (b). Solid points indicate measurement results, open circles—calculations for different thermal boundary conductance values. Interface roughness in calculations was equal to optimal-fit value.

Calculated phonon scattering times at 300 K for 11.2 nm period superlattice are presented in figure 5 for Al$_{0.28}$Ga$_{0.72}$N (panel (a)) and GaN (panel (b)) layers, interface roughness equals 0.08 nm. One has to keep in mind, that shown on the figures phonon-phonon normal scattering is not a resistive process, and it indirectly influences thermal conductivity. For both layers impact of Umklapp processes on thermal conductivity is low; alloy-scattering is a dominant scattering mechanism for AlGaN (due the presence of Al atoms), while for GaN its influence on phonon transport is even lower than of the Umklapp scattering. Phonon-boundary scattering prevails other scattering processes for GaN for both in-plane and cross-plane directions, whereas boundary scattering together with the point-defect phonon scattering are the dominant phonon scattering mechanisms for AlGaN layer.

Dependence of thermal conductivity on Al mass fraction at 300 K is shown in figure 6; results for AlGaN films (with thickness less than 1000 nm) from references [19, 21–24, 52, 53], AlN/GaN superlattice [25] and from our work for
AlGaN/GaN superlattices are presented. One can see, that values of the in-plane thermal conductivity of AlGaN/GaN superlattices are similar to the one of the AlGaN films, while the cross-plane thermal conductivity is much lower than the thermal conductivity of the films. This can be connected with the increased influence of phonon-boundary and phonon-alloying element scattering processes on the cross-plane thermal conductivity.

5. Conclusions

In-plane and cross-plane thermal conductivity of AlGaN/GaN superlattices was investigated both theoretically and experimentally. Decrease in thermal conductivity with reduction of period thickness was observed and is attributed to increasing role of phonon-boundary scattering. Results of calculation using a model, which takes into account dependence of phonon-boundary scattering rate on phonon wavelength, agree well with measured in-plane thermal conductivity. For the cross-plane thermal conductivity, neglecting of the thermal boundary conduction leads to overestimation of thermal conductivity, while accounting it leads to the underestimation. Thermal boundary conductance has to be 2–3 times higher than the one, calculated with AMM, in order to provide an agreement of calculations and experimental results. Analysis of scattering time for different phonon scattering processes showed, that dominating mechanisms are boundary scattering and, for AlGaN layer, also an alloy disorder scattering. Measured in-plane thermal conductivity of AlGaN/GaN superlattices are similar to the one of the AlGaN films, while the cross-plane thermal conductivity is much lower. Presented in this work results are an important step for a better understanding of heat dissipation processes in AlGaN/GaN-based devices.

Acknowledgments

This work was supported by Team Tech/2016-3/16 project. Authors are grateful to Sandeep Gorantla for TEM imaging and Dr Damian Smyrski for SEM measurements.

ORCID IDs

A Filatova-Zalewska @ https://orcid.org/0000-0002-2710-8762

References

[1] Asgari A, Ahmadi E and Kalafi M 2009 AlGaN/GaN multi-quantum-well ultra-violet detector based on p-i-n heterostructures Microelectron. J. 40 104–7
[2] Figge S, Kröncke H, Hommel D and Epelbaum B M 2009 Temperature dependence of the thermal expansion of AlN Appl. Phys. Lett. 94 101915
[3] Hirayama H, Maeda N, Fujikawa S, Toyoda S and Kamata N 2014 Recent progress and future prospects of AlGaN-based high-efficiency deep-ultraviolet light-emitting diodes Japan. J. Appl. Phys. 53 100209
[4] Ren Z, Yu H, Liu Z, Wang D, Xing C, Zhang H, Huang C, Long S and Sun H 2020 Band engineering of III-nitride-based deep-ultraviolet light-emitting diodes: a review J. Phys. D: Appl. Phys. 53 073002
[5] Levinstein M E, Rumyantsev S L, Gaska R, Yang J W and Shur M S 1998 AlGaN/GaN high electron mobility field effect transistors with low 1/f noise Appl. Phys. Lett. 73 1089–91
[6] Nahhas A M 2019 Review of AlGaN/GaN HEMTs based devices Am. J. Nanomater. 7 10–21
[7] Sheu J K, Chen P C, Shin C L, Lee M L, Liao P H and Lai W C 2016 Manganese-doped AlGaN/GaN heterojunction solar cells with intermediate band absorption Sol. Energy Mater. Sol. Cells 157 727–32
[8] Bai J, Gong Y P, Li Z, Zhang Y and Wang T 2018 Semi-polar InGaN/GaN multiple quantum well solar cells with spectral response at up to 560 nm Sol. Energy Mater. Sol. Cells 175 47–51
[9] Pantha B N, Dahal R, Li J, Lin J Y, Jiang H X and Pomeranke G 2008 Thermoelectric properties of InxGa1−xN alloys Appl. Phys. Lett. 92 042112
[10] Sztiein A, Haberstroh J, Bowers J E, Denbaars S P and Nakamura S 2013 Calculated thermoelectric properties of InxGa1-xN, InxAl1-xN, and AlGaxN1-x J. Appl. Phys. 113 183707
[11] Tritt T M 2004 Thermal Conductivity (New York: Springer) (https://doi.org/10.1007/b136496)
[12] Sichel E K and Pankove J J 1977 Thermal conductivity of GaN, 25–360 K J. Phys. Chem. Solids 38 330
[13] Zou J, Kotchetkov D, Balandin A A, Florescu D I and Pollak F H 2002 Thermal conductivity of GaN films: effects of impurities and dislocations J. Appl. Phys. 92 2534–9
[14] Jezowski A, Daniłchenko B A, Boćkowski M, Grzegory I, Krukowski S, Suski T and Paszkiewicz T 2003 Thermal conductivity of GaN crystals in 4.2–300 K range Solid State Commun. 128 69–73
[15] Mion C, Muth J F, Preble E A and Hahser D 2006 Accurate dependence of gallium nitride thermal conductivity on dislocation density Appl. Phys. Lett. 89 092123
[16] Beechem T E, McDonald A E, Fuller E J, Talin A A, Rost C M, Maria J P, Gaskins J T, Hopkins P E and...
Allermand A A 2016 Size dictated thermal conductivity of GaN J. Appl. Phys. 120 095104
[17] Slomski M, Paskov P P, Leach J H, Muth J F and Paskova T 2017 Thermal conductivity of bulk GaN grown by HVPE: effect of Si doping Phys. Status Solidi 254 1600713
[18] Zheng Q, Li C, Rai A, Leach J H, Brodoo D A and Cahill D G 2019 Thermal conductivity of GaN, GaN 71, and SiC from 150 K to 850 K Phys. Rev. Mater. 3 014601
[19] Daly B C, Maris J H, Nurminsky A V, Kaball M and Han J 2002 Optical pump-and-probe measurement of the thermal conductivity of nitride thin films J. Appl. Phys. 92 3820–4
[20] Liu W and Balandin A A 2004 Temperature dependence of thermal conductivity of AlGaN, thin films measured by the differential 3ω technique Appl. Phys. Lett. 85 5230–2
[21] Liu W and Balandin A A 2005 Thermal conduction in AlxGa1–x N alloys and thin films J. Appl. Phys. 97 073710
[22] Su Z 2014 Nanoscale heat transport and interface properties of group III nitride semiconductor nanostructures PhD Thesis Carnegie Mellon University
[23] Slomski M J 2017 Thermal conductivity of group-III nitrides and oxides PhD Thesis North Carolina State University
[24] Filatova-Zalewska A, Litwcki Z, Suski T and Jeziowsk A 2020 Thermal conductivity of thin films of gallium nitride, doped with aluminium, measured with 3ω method Solid State Sci. 101 106105
[25] Koh Y K, Cao Y, Cahill D G and Jena D 2009 Heat-transport mechanisms in superlattices Adv. Funct. Mater. 19 610–5
[26] Cahill D G 1990 Thermal conductivity measurement from 30 to 750 K: the 3ω method Rev. Sci. Instrum. 61 802–8
[27] Chen G, Zhou S Q, Yao D Y, Kim C J, Zheng X Y, Liu Z L, Wang K L, Sun X and Dresselhaus M S 1998 Heat conduction in alloy-based superlattices Int. Conf. on Thermoelectrics, ICT, Proc. (IEEE) pp 202–5
[28] Borca-Tasciuc T, Song D, Liu J L, Chen G, Wang K L, Sun X, Dresselhaus M S, Radetic T and Grönsky R 1999 Anisotropic thermal conductivity of a Si/Ge superlattice Mater. Res. Soc. Symp.—Proc. 545 473–8
[29] Liu W L, Borca-Tasciuc T, Chen G, Liu J L and Wang K L 2001 Anisotropic thermal conductivity of Ge quantum-dot and symmetrically strained Si/Ge superlattices J. Nanosci. Nanotechnol. 1 39–42
[30] Borca-Tasciuc T, Kumar A R and Chen G 2001 Data reduction in 3ω method for thin-film thermal conductivity determination Rev. Sci. Instrum. 72 2139–47
[31] Klimek S J and McClintock F A 1953 Describing uncertainties in single-sample experiments Mech. Eng. 75 3–8
[32] Mei S and Knezevic I 2015 Thermal conductivity of III–V semiconductor superlattices J. Appl. Phys. 118 175101
[33] Alvarez F X, Alvarez-Quntana J, Jou D and Viejo J R 2010 Analytical expression for thermal conductivity of superlattices J. Appl. Phys. 107 084303
[34] Callaway J 1959 Model for lattice thermal conductivity at low temperatures Phys. Rev. 113 1046–51
[35] Ziman J M 1960 Electrons and Phonons (Oxford: Clarendon)
[36] Maznev A A 2015 Boundary scattering of phonons: specularity of a randomly rough surface in the small-perturbation limit Phys. Rev. B 91 134306
[37] Abeles B 1963 Lattice thermal conductivity of disordered semiconductor alloys at high temperatures Phys. Rev. 131 1906–11
[38] Cahill D G and Pohl R O 1988 Lattice vibrations and heat transport in crystals and glasses Annu. Rev. Phys. Chem. 39 93–121
[39] Little W A 1959 The transport of heat between dissimilar solids at low temperatures Can. J. Phys. 37 334–49
[40] Swartz E T and Pohl R O 1989 Thermal boundary resistance Rev. Mod. Phys. 61 605–68
[41] Aksamija Z and Knezevic I 2013 Thermal conductivity of Si1–xGex/Si1–yGey superlattices: competition between interfacial and internal scattering Phys. Rev. B 88 055707
[42] Terentzidis K, Chantrempe P, Duquesne J Y and Saci A 2010 Thermal conductivity of GaAs/AlAs superlattices and the puzzle of interfaces J. Phys. Condens. Matter 22 475001
[43] Latour B, Velz S and Chalopin Y 2014 Microscopic description of thermal-phonon coherence: from coherent transport to diffuse interface scattering in superlattices Phys. Rev. B 90 014307
[44] Tian Z, Esfarjani K and Chen G 2014 Green’s function studies of phonon transport across Si/Ge superlattices Phys. Rev. B 89 235307
[45] Kothari K, Malhotra A and Maldovan M 2019 Cross-plane heat conduction in III–V semiconductor superlattices J. Phys. Condens. Matter 31 345301
[46] Kothari K and Maldovan M 2018 Analysis of in-plane thermal phonon transport in III–V compound semiconductor superlattices Nanoscale Microscale Thermophys. Eng. 22 239–53
[47] Lee W Y, Lee J H, Ahn J Y, Park T H, Park N W, Kim G S, Park J S and Lee S K 2017 Anisotropic temperature-dependent thermal conductivity by an Al2O3 interlayer in Al0.05G0.95O3/ZnO superlattice films Nanotechnology 28 154051
[48] Feng Y and Liang X G 2015 Modified series model for cross-plane thermal conductivity of short-period Si/Ge superlattices Sci. China Phys., Mech. Astron. 58 60701
[49] Yang B, Liu W L, Liu J L, Wang K L and Chen G 2002 Measurements of anisotropic thermoelectric properties in superlattices Appl. Phys. Lett. 81 3588–90
[50] Ju J, Sun B, Haunschild G, Loitsch B, Stoib B, Brandt M S, Stutzmann M, Koh Y K and Kohlmüller G 2016 Thermoelectric properties of In-rich InGaN and InN/InGaN superlattices AIP Adv. 6 045216
[51] Capinski W S, Maris H J, Ruf T, Cardona M, Ploog K and Katzer D S 1999 Thermal-conductivity measurements of GaAs/AlAs superlattices using a picosecond optical pump-and-probe technique Phys. Rev. B 59 8105–13
[52] Koh Y R, Shirazi-Hd M, Vermeersch B, Mohammed A M S, Shao J, Pernot G, Bahk J H, Manfra M J and Shakouri A 2016 Quasi-ballistic thermal transport in Al0.05G0.95O3 thin film semiconductors Appl. Phys. Lett. 109 243107
[53] Mitterhuber L, Hammer R, Dengg T and Spitaler J 2020 Thermal characterization and modelling of AlGaN-GaN multilayer structures for HEMT applications Energies 13 2363
[54] Adachi S 1983 Lattice thermal resistivity of III–V compound alloys J. Appl. Phys. 54 1844–8
[55] Adachi S 2007 Lattice thermal conductivity of group-IV and III–V semiconductor alloys J. Appl. Phys. 102 063502