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Quantitative scanning thermal microscopy of ErAs/GaAs superlattice structures grown by molecular beam epitaxy

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A proximal probe-based quantitative measurement of thermal conductivity with \( \sim 100–150 \text{nm} \) lateral and vertical spatial resolution has been implemented. Measurements on an ErAs/GaAs superlattice structure grown by molecular beam epitaxy with \( 3\% \) volumetric ErAs content yielded thermal conductivity at room temperature of \( 9 \pm 2 \text{W/m K} \), approximately five times lower than that for GaAs. Numerical modeling of phonon scattering by ErAs nanoparticles yielded thermal conductivities in reasonable agreement with those measured experimentally and provides insight into the potential influence of nanoparticle shape on phonon scattering. Measurements of wedge-shaped samples created by focused ion beam milling provide direct confirmation of depth resolution achieved. © 2013 American Institute of Physics.

Incorporation of nanoparticles or other nanostructures in crystalline semiconductor materials is emerging as a highly effective approach for engineering thermal transport behavior, as the resulting increase in phonon scattering can lead to large reductions in thermal conductivity that are desirable for thermoelectric device applications.1–5 Furthermore, the presence of such structures within other types of semiconductor devices may be expected to influence thermal transport and consequently thermal management strategies in those devices.1,2 In this context, III-V semiconductor/rare earth-V nanocomposite materials are of particular interest due to the potential for epitaxial incorporation of rare earth-V nanoparticles in a single-crystal III-V semiconductor to reduce thermal conductivity, and interest in such nanocomposite materials encompasses a variety of device applications including multijunction solar cells,6 high-speed modulators,7 thermoelectrics,8,9 and fast photoconductors for THz sources and receivers.8,10 However, methods for quantitative assessment of thermal transport behavior at the nanoscale remain challenging.

In this letter, we report studies in which the \( 3\omega \) technique for measuring thermal conductivity14–13 was implemented using a functionalized probe in an atomic force microscope14–19 and used to obtain quantitative measurements of thermal conductivity in an ErAs/GaAs superlattice structure grown by molecular beam epitaxy. This approach allows us to achieve very high spatial resolution in measuring thermal conductivity of \( \sim 100 \text{nm} \) laterally and \( \sim 150 \text{nm} \) in depth, limited by the size of the probe tip apex. With calibration using materials of known thermal conductivity, quantitative accuracy of approximately \( \pm 20\% \) was achieved over the range of thermal conductivities of interest in this work. We find that incorporation of ErAs nanoparticles with even a low \( (\sim 3\%) \) average concentration of ErAs leads to a reduction in room-temperature thermal conductivity by approximately a factor of five, from \( \sim 50 \text{W/m K} \) in GaAs to \( 9 \pm 2 \text{W/m K} \) in the ErAs/GaAs superlattice, and show that this result is in reasonable accord with numerical modeling of phonon scattering by ErAs nanoparticles embedded in GaAs.

The ErAs/GaAs superlattice structure employed in this work was grown by solid-source molecular beam epitaxy (MBE) in a Varian Gen II system. The sample structure consisted of a 150 nm undoped GaAs buffer layer grown at 580°C on a semi-insulating GaAs (001) substrate, followed by a 200 nm ErAs/GaAs superlattice consisting of 40 repetitions of 0.5 monolayer (ML) ErAs and 5 nm GaAs grown at 450°C. Under these growth conditions, the ErAs layers form 3–4 ML (\( \sim 0.9–1.1 \text{ nm} \)) high nanoparticles with diameters of \( \sim 3 \text{ nm} \), leading to an average fill factor of 0.14 for each ErAs layer and allowing high-quality overgrowth of the ErAs nanoparticle seeded by the exposed GaAs remaining after deposition of each ErAs layer.20

Scanning thermal microscopy measurements were performed under ambient conditions using a Bruker Dimension ICON scanning probe microscopy system equipped with a functionalized probe in which a thin patterned Pd film on the probe tip served as a localized heater and thermometer. In a manner analogous to the standard \( 3\omega \) measurement in a planar geometry,11–13 an electrical excitation signal at frequency \( \omega \) induces variations in the resistance of the functionalized probe tip, corresponding to changes in its temperature, at frequency \( 3\omega \) that are detected using a Wheatstone bridge circuit configuration and lock-in amplifier. The measurement apparatus and experimental geometry are shown schematically in Fig. 1(a).

The functionalized probe was connected to one arm of the Wheatstone bridge circuit that also included two resistors, \( R_1 \) and \( R_2 \), of known value and one variable resistor used to balance the bridge. The functionalized probe tip, shown in Fig. 1(b), incorporated a Pd thin-film resistor, deposited on SiO\(_2\), which served as a heater and thermometer. An input voltage signal at frequency \( \omega \) was used to excite the bridge circuit, and the \( 3\omega \) frequency component of the voltage difference between opposite nodes, \( V_p-V_n \), was detected by a lock-in amplifier and used to monitor the thermal behavior of the probe tip. By modeling the thermal transport between the probe tip apex and the sample, it was possible to extract information about the sample thermal conductivity. Quantitative

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determination of sample thermal conductivity was achieved via a calibration process in which (i) samples of known thermal conductivity, e.g., GaAs, Si, and SiO$_2$, were measured along with the actual sample of interest; (ii) the $3\omega$ component of voltage response was modeled as a function of sample thermal conductivity; (iii) the model was calibrated to data obtained for the samples of known thermal conductivity; (iv) the unknown sample thermal conductivity was obtained from its measured $3\omega$ response and the model calibrated to samples of known thermal conductivity.

We have adapted a thermal model employed in previous work on scanning thermal microscopy$^{14,18}$ to determine the thermal conductivity in our samples. In this approach, the probe tip was modeled using the transient fin equation to determine the probe tip temperature and equivalent thermal contact resistance, $R_{\text{eq}}$, between the probe tip and sample. Heat transfer between the probe tip and sample can occur via solid-solid conduction, conduction through the liquid meniscus that forms between the probe tip and sample, and conduction through the air gap surrounding the tip-sample junction.$^{21,22}$ The liquid meniscus is formed under ambient measurement conditions by water molecules absorbed on the sample and tip surfaces. We modeled $R_{\text{eq}}$ by including two thermal resistance components in parallel—the electroconstriction resistance associated with the solid-solid contact between probe tip and sample surface, $R_c$, and the thermal resistance associated with the water meniscus, $R_m$.

Depending on the relative magnitudes of the solid-solid contact radius, $r_c$, and phonon mean free path, $\lambda_{\text{ph}}$, the electroconstriction resistance may include various combinations of diffusive (for $r_c \gg \lambda_{\text{ph}}$) and ballistic (for $r_c \ll \lambda_{\text{ph}}$) components; it has been shown that the sum of these two components provides a good approximation to obtain the total electroconstriction resistance.$^{23}$ We used the diffuse mismatch model$^{23,24}$ to calculate the ballistic resistance component for two adjoining solid materials, and the estimated ballistic component was two orders of magnitude smaller than the diffusive component so the diffusive component dominates in our work. $R_c$ is then computed by modeling the tip-sample contact as a sphere in contact with a flat surface, as shown schematically in Fig. 1(c), for which the thermal resistance is given by$^{23}$

$$R_c = \frac{1}{4\pi r_c} \left( \frac{1}{\kappa_p} + \frac{1}{\kappa_s} \right),$$  

(1)

where $\kappa_p$ and $\kappa_s$ are the thermal conductivities of the probe tip and sample, respectively. $R_m$ is computed assuming the same geometry for the probe tip and sample and is given by$^{23,25}$

$$\frac{1}{R_m} = \frac{1}{\Delta T_{\text{max}}} \int_{b_{\text{min}}}^{b_{\text{max}}} \frac{\kappa_m \Delta T(r)}{h(r)2\pi r dr}$$

$$= 2\pi \kappa_m \left\{ \sqrt{r_2^2 - r^2} + r_1 \log \left( \sqrt{r_2^2 - r^2} - r_1 \right) \right\}_{b_{\text{min}}}^{b_{\text{max}}},$$  

(2)

where $\kappa_m$ is the thermal conductivity of the water forming the meniscus and $r_1$, $b_{\text{min}}$, and $b_{\text{max}}$ are the tip radius, minimum-, and maximum radii of the water meniscus, as shown in Fig. 1(c). $\Delta T(r)$ is the position dependent temperature difference between the thermal probe and substrate, which assumes a maximum values $\Delta T_{\text{max}}$. In our calculations, we assume the probe is isothermal in the immediate vicinity the tip apex, so that $\Delta T(r) = \Delta T_{\text{max}}$. $R_{\text{eq}}$ is then given by

$$R_{\text{eq}} = \frac{R_c R_m}{R_c + R_m},$$  

(3)

Experimental measurement of the $3\omega$ frequency component of $V_p - V_r$, as shown in Fig. 1(a), yields the temperature of the probe tip, from which the sample thermal conductivity can be determined using the model described above. For modeling of the amplitude and phase of $V_{3\omega}$, we also account for the NiCr current limiters integrated into the thermal probe tip using a first order low-pass filter function.$^{18}$

To provide the calibration necessary to obtain a quantitative measurement of thermal conductivity for the ErAs/GaAs superlattice, multiple measurements were performed on each of the following five samples: (i) $15 \mu$m of SiO$_2$ formed by thermal oxidation; (ii) a GaAs (001) undoped wafer; (iii) a crystalline Si (001) n-type wafer; (iv) a silicon-on-insulator (SOI) wafer with Si layer thickness of 1000 nm and oxide thickness of 1000 nm; and (v) the ErAs/GaAs superlattice sample. Prior to measurement, all samples were cleaned with acetone and isopropyl alcohol followed by a dry
nitrogen spray. Figure 2(a) shows $(V_p - V_r)_{3\omega} \equiv V_{3\omega}$ measured as a function of frequency and with an excitation amplitude $V_0 = 0.65$ V for all samples. Small, but clearly discernible, differences are evident among the samples measured, as made evident by the magnified vertical axis employed in the signal range corresponding to frequencies of 100 Hz and below. Figure 2(b) shows the measured and modeled amplitude and phase of $V_{3\omega}$ as functions of frequency for the crystalline Si sample. A comparison of Figs. 2(a) and 2(b) shows that all samples exhibit the same characteristic dependence of $V_{3\omega}$ on frequency, and in Fig. 2(b) the comparison of experimental and modeled signal amplitude confirms the excellent agreement, over all measured frequencies, between the measured and modeled signal values. Fig. 2(c) shows the amplitude of $V_{3\omega}$ at 50 Hz modeled as a function of sample thermal conductivity, along with the measured signal values for the five materials characterized. The vertical error bars in Fig. 2(c) correspond to multiple measurements performed for each material. For SiO$_2$, GaAs, Si, and SOI, the sample thermal conductivities were assumed to correspond to their established values (hence the absence of horizontal error bars), and agreement between the numerical model and experimental measurements was excellent. This enabled us to use the measured amplitude of $V_{3\omega}$ for the ErAs/GaAs superlattice structure, combined with the numerical model, to obtain the superlattice thermal conductivity value of $9 \pm 2$ W/m K indicated in the Fig. 2(c). The uncertainty given for this value of the superlattice thermal conductivity was obtained by taking the statistical uncertainty in the measured values of $V_{3\omega}$ for that sample and fitting the upper and lower end of the statistical range to the thermal model.

To understand the influence of phonon scattering by ErAs nanoparticles on the ErAs/GaAs superlattice thermal conductivity, we have also performed theoretical estimates of the relevant scattering processes using the Callaway model. At room temperature, it is anticipated that the Umklapp and mass difference scattering processes are dominant rather than normal scattering process. The combined phonon relaxation time $\tau_e$ is given, using Matthiessen’s rule, by

$$\frac{1}{\tau_e} = \frac{1}{\tau_{U}} + \frac{1}{\tau_{M}} + \frac{1}{\tau_{e-ph}} + \frac{1}{\tau_{np}},$$

where $\tau_U$, $\tau_M$, $\tau_{e-ph}$, and $\tau_{np}$ are, respectively, relaxation times associated with Umklapp, mass difference (isotopes), electron-phonon, and ErAs nanoparticle scattering. $\tau_U$, $\tau_M$, and $\tau_{e-ph}$ are computed using established parameters from the literature. We have also attempted to account, at least approximately, for varying shapes of the ErAs nanoparticles in the computation of phonon scattering. For the growth conditions employed here, the ErAs is expected to form nanoparticles ~1.5 nm in radius and 3–4 ML (~1 nm) high, leading to a disk–like shape. To account for this shape in the model, we assume that phonon scattering scales with the nanoparticle cross-sectional area projected onto the plane normal to the phonon wave vector; for a phonon whose wave vector is at an angle $\theta$ to the (001) nanoparticle surface, this yields factor of $\cos(\theta)$ in the scattering cross section with an additional correction for the disk thickness. An effective scattering cross-section was then calculated by averaging over angles ranging from 0$^\circ$ to 90$^\circ$. For the expected ErAs average nanoparticle radius of 1.5 nm with a standard deviation of 1 nm and ErAs content of 3%, this model yields a thermal conductivity of ~15 W/m K, reasonably close to the experimentally measured value given the approximate nature of the model, uncertainties in the model parameters, and lack of free parameters.

Finally, to assess the depth sensitivity of the proximal probe $3\omega$ measurement and verify that these measurements were sensitive to the thermal transport properties of only the superlattice structure and not the underlying GaAs buffer layer and substrate, a wedge-shaped sample structure was prepared using focused ion beam (FIB) milling, as shown schematically in Fig. 3(a). A gallium ion beam at 30 keV...
was used to expose a cross-section of the ErAs/GaAs superlattice and underlying GaAs layers at an angle of \(\sim 6^\circ\), producing a wedge structure in which the ErAs/GaAs superlattice thickness at the sample surface varied continuously from 200 nm to 0 nm over a lateral distance of 2000 nm. Figure 3(b) shows an atomic force micrograph and 3\(\omega\) signal image at a fundamental frequency of 850 Hz, obtained simultaneously, of wedge structure across surface region with ErAs/GaAs superlattice thickness varying from 200 nm to 0 nm. White dotted lines indicate regions from which plots in (c) were extracted. (c) Plots of voltage signal extracted from the images in Fig. 3(b) along a direction parallel to, and within the area bounded by, the white dotted lines indicated in the images. The regions corresponding to the ErAs/GaAs superlattice (001) surface and the exposed cross-sections of the superlattice and underlying GaAs are indicated. Each point shown in Fig. 3(c) represents the signal value averaged along a 1500 nm line parallel to the white dotted lines shown in Fig. 3(b). The error bars shown for \(V_{3\omega}\) amplitude in Fig. 3(c) are associated with the signal variations measured along each such line during sample scanning; however, the average values shown clearly reveal the trend in thermal response as a function of location along the wedge profile. As can be seen in Fig. 3(c), the measured \(3\omega\) signal and therefore the sample thermal conductivity remained constant for the ErAs/GaAs superlattice (001) surface and the superlattice cross-section until the superlattice thickness directly beneath the tip was reduced to \(\sim 150\) nm. The measured \(3\omega\) signal then decreased steadily, corresponding to increasing thermal conductivity, due to decreasing superlattice thickness, reaching an approximately constant value with the probe tip over the GaAs surface or an ErAs/GaAs superlattice thickness of \(\sim 20\) nm or less. The difference in signal values between those shown in Figs. 2 and 3 arises due to the lateral and depth resolution of \(\sim 100–150\) nm for lower ErAs/GaAs superlattice thicknesses, the measurement probes the combined thermal transport properties of the ErAs/GaAs superlattice and underlying GaAs, eventually being dominated by the higher thermal conductivity of the GaAs for very small superlattice thicknesses or when the superlattice is completely absent. The high spatial resolution, both laterally and in depth, afforded by this technique can be particularly advantageous in characterization of thin film materials and nanostructures in which variation in thermal behavior at these length scale are present.

In summary, we have used a \(3\omega\) thermal conductivity measurement implemented in a scanning probe microscope to characterize thermal conductivity in an ErAs/GaAs superlattice. By performing detailed numerical modeling of thermal transport at and near the probe tip-sample interface and calibrating measured signals using samples of known thermal conductivity, we are able to perform quantitative measurements of thermal conductivity in unknown samples with lateral and depth resolution of \(\sim 100–150\) nm. We obtained a value of \(9 \pm 2\) W/m K for thermal conductivity at room temperature in an ErAs/GaAs superlattice with \(\sim 3\%\) average ErAs content, approximately 5 times lower than that for GaAs. Numerical modeling of phonon scattering by ErAs nanoparticles yielded values for thermal conductivity in good agreement with those measured experimentally. The level of spatial resolution we demonstrate is much higher than that attainable in \(3\omega\) measurements performed using

FIG. 3. (a) Schematic diagram and scanning electron micrograph of focused-ion-beam-milled wedge sample structure showing the milling geometry and cross-sectional ramp to expose the ErAs/GaAs superlattice and underlying GaAs; the approximate location of images in (b) is indicated by the white dotted line. (b) Atomic force topograph and 3\(\omega\) signal image, obtained simultaneously, of wedge structure across surface region with ErAs/GaAs superlattice thickness varying from 200 nm to 0 nm. White dotted lines indicate regions from which plots in (c) were extracted. (c) Plots of 3\(\omega\) signal amplitude, standard deviation indicated by error bars, along a 1500 nm line parallel to the white dotted lines shown in (b).
more conventional geometries and is anticipated to enable future studies of thermal conductivity at nanoscale dimensions in a variety of solid-state nanostructures.

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