Thermal Conductivity of InAs/GaSb Type II Superlattice

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The cross-plane thermal conductivity of a type II InAs/GaSb superlattice (T2SL) is measured from 13 K to 300 K using the 3ω method. Thermal conductivity is reduced by up to two orders of magnitude relative to the GaSb bulk substrate. The low thermal conductivity of around 1 W/m K to 8 W/m K may serve as an advantage for thermoelectric applications at low temperatures, while presenting a challenge for T2SL interband cascade lasers and high-power photodiodes. We describe a power-law approximation to model nonlinearities in the thermal conductivity, resulting in increased or decreased peak temperature for negative or positive exponents, respectively.

Key words: Thermal conductivity, type II superlattice, interband cascade lasers, photodiode, thermoelectric

INTRODUCTION

InAs/GaSb type II broken-gap superlattices (T2SL) have been successfully developed for use in long-wavelength (LWIR) and midwave (MWIR) infrared detectors1–5 with band-engineered cutoff wavelengths and a reduction in dark current compared with direct-gap bulk semiconductors. High-power LWIR and MWIR interband cascade lasers (ICLs) and photodiodes (PDs) based on T2SL band-structure engineering6–13 also offer tunable infrared light emission. For high-power IR emitters, heat needs to be carried away from the active region to allow longer Auger lifetime, lower thresholds, and lower power loss. For IR detectors, cooling below room temperature is usually required to reduce electrical noise due to thermal generation of carriers. It is therefore important to have good understanding of the thermal conductivity of this artificial material, to understand performance parameters over a wide range of operating temperatures. Recently, efforts by the authors have also identified the T2SL as a candidate material for low-temperature Peltier cooling14 based on the large Seebeck coefficients that have been reported at cryogenic temperatures,15 but measurements of the thermal conductivity at these temperatures were lacking. In this work, we measured the cross-plane thermal conductivity of T2SLs from 13 K to 300 K using the 3ω method16–18 and present a power-law approximation for modeling thermal conductivity over large thermal gradients expected to occur in such low-thermal-conducting materials.

EXPERIMENTAL RESULTS

The two different T2SLs studied in this work were grown by molecular beam epitaxy on GaSb substrates. Because this material was designed for p-i-n detectors, it consists of a 0.5-μm GaSb p+ (~10^18 cm^-3) buffer layer, followed by a 0.5-μm T2SL p+ (~10^18 cm^-3) region, a 2-μm undoped T2SL layer, a 0.5-μm T2SL n+ (~10^18 cm^-3) region, and a 10-nm Si-doped InAs n+ capping layer. T2SL-1 is composed of 12 monolayers (MLs) of InAs and 8 MLs of GaSb per period. T2SL-2 is composed of 19 MLs of InAs and 8 MLs of GaSb per period.*

Following standard 3ω sample preparation, the thermal conductivity of a sample including the layer of interest is measured relative to a reference sample without the layer. Thus, the T2SL is wet-etched away from half the sample with a solution of citric acid and phosphoric acid plus peroxide.

*Protocol names: T2SL-1 = 1554; T2SL-2 = 2168A.
An insulating SiO₂ layer of 150 nm is deposited using plasma-enhanced chemical vapor deposition (PECVD) to prevent an electrical short circuit through the conducting substrate. Then 200-nm-thick gold heater–thermometer filaments are deposited atop a 3-nm Ti adhesion layer using e-beam evaporation on both etched and unetched regions. The filament shown in the inset of Fig. 1b is 3.6 mm long and 30 μm wide, much wider than the 3 μm T2SL thickness, so that the heat flow through the T2SL obeys the one-dimensional thermal diffusion equation.¹⁸

According to the 3ω method,¹⁶–¹⁸ by sending a current excitation at frequency ω through the gold filament, heating power P is induced at frequency 2ω, leading to thermal variation ΔT at the same frequency and ultimately a four-point voltage V₃ω at frequency 3ω proportional to the temperature difference via the thermal coefficient of Au.¹⁶,¹⁷ The thermal difference ΔT = ΔTₜ + ΔTₛ can have a frequency-dependent substrate contribution and a frequency-independent thin-film contribution,

\[ ΔT_{\text{t}}(ω) = \frac{-P}{lπκ_{\text{t}}ω} \ln(2ω) + C, \]

\[ ΔT_{\text{s}} = \frac{P}{κ_{\text{s}}} t \frac{ω}{l}, \]

where κₙₙ is the thermal conductivity of the GaSb substrate, w and l are the width and length of the Au filament heater, and C is a constant offset which includes the SiO₂ layer contribution. For the T2SL film, κᵣ and t are the film thermal conductivity and thickness, respectively.

We measured the sample in an Oxford variable-temperature insert (VTI) helium gas flow cryostat from 300 K down to 13 K, using standard lock-in techniques. Since there are background 3ω voltages from the lock-in power source and nonlinear components in the measurement circuit and in the lock-in A–B input channels, we also measured a reference background 3ω signal with a low-thermal-coefficient resistor of equal resistance as the gold filament.

By measuring the slope of the temperature difference ΔT as a function of log frequency,¹⁶,¹⁷ we can deduce the substrate thermal conductivity and thereby confirm the reliability of our measurements. In Fig. 2, we compare our measured GaSb substrate thermal conductivity (solid circles) with previously published GaSb bulk thermal conductivity (open circles),¹⁹,²⁰ indicating excellent agreement.

The T2SL cross-plane thermal conductivity κᵣ is deduced from the thermal difference ΔTᵣ, plotted as solid triangles in Fig. 2. Previous studies of superlattice thermal conductivities have shown that the superlattice thermal conductivity is significantly reduced from those of their constituent bulk materials, resulting from phonon interface scattering, reduced group velocity from the modified phonon dispersion relation, and strain-relaxation-induced high density of dislocations.²¹–²³ The T2SL value is reduced by two orders of magnitude compared with the bulk substrate thermal conductivities for GaSb bulk (open circles). We note that the suppression is much greater, up to as much as 3.5 orders of magnitude, when compared with InAs bulk (open squares).

**DISCUSSION**

To estimate the T2SL thermal conductivity at arbitrary temperatures, we provide the equation for the solid-line empirical fit to the measured T2SL thermal conductivity in Fig. 2.

\[ \log κ = \log κ_0 - B \left[ \log \left( \frac{T}{T_m} \right) \right]^2 + C \left[ \log \left( \frac{T}{T_m} \right) \right]^3 \]

**Fig. 1.** Temperature change ΔT versus frequency f measured on T2SL-2 by the 3ω method for the T2SL + SiO₂ + GaSb substrate (filled symbols) and for SiO₂ + GaSb substrate (open symbols): (a) at 15 K and 300 K, and (b) at 80 K and 212 K. Inset: picture of the sample, with left half etched to substrate and right half unetched. Two Au heater–thermometer lines are deposited on each side, with current contact pads at top/bottom and voltage contacts in between.

**Fig. 2.** Cross-plane thermal conductivity for T2SL samples (solid triangles). Measured GaSb substrate thermal conductivity is shown by solid circles. Published data for bulk thermal conductivity of InAs and GaSb are shown for comparison as open squares and open circles, respectively. The solid line is a fitted polynomial for the average value of T2SL thermal conductivity described in the text.
with maximum thermal conductivity $\kappa_m = 6.954$ W/mK at $T_m = 74$ K, $B = 1.0312$, and $C = 0.53042$.

To improve device performance, it is useful to model the thermal distribution within the active layer of an ICL or PD. With poor thermal conductivity, one can expect large thermal gradients across the T2SL layer, so it is useful to develop an analytical estimate of the thermal profile including large temperature drops. We do so below by introducing a power-law approximation to the temperature dependence of the thermal conductivity.

The thermal profile can be determined from the power density generated per unit volume for the various devices of interest, namely PDs and ICLs. For an infrared PD the power density due to Joule heating is

$$P = \varepsilon J,$$

where the electric field $E$ across the T2SL emitting layer is assumed uniform, $J$ is the current density, and the light output power is neglected. For continuous-wave (CW) lasers, one can estimate the heat dissipated at threshold assuming that almost all input power is dissipated as heat

$$P = (E_{32} + \Delta)J_{th}/eL_p,$$  

where $J_{th}$ is the threshold current density, $E_{32}$ is the energy of the optical transition, $\Delta$ is the energy separation between the ground state of the injector and the lower laser level of the previous active region, and $L_p$ is the length of one period of ICL active region and injector.

Using Eqs. 4 and 5, the thermal profile in the active region becomes

$$P = \nabla \cdot (-\kappa \nabla T).$$

For a substrate-side mounted device, the primary heat dissipation is through the GaSb substrate, modeled as a one-dimensional (1D) thermal diffusion problem. If, for the moment, a constant thermal conductivity $\kappa_0$ is assumed, the solution to Eq. 6 takes the simple form

$$\Delta T(x) = -\frac{1}{2 \kappa_0} x^2 + \frac{dT}{dx} \bigg|_0 x,$$

with boundary conditions $\Delta T(0) = 0$ and $dT/dx(0) = d^2 T/dx^2 \bigg|_0$.

However, we arrive at a more accurate estimate of the thermal profile at high powers if we include the temperature dependence of $\kappa(T)$. By inspection of the T2SL log–log plot in Fig. 2, for large ranges of temperature above 150 K and below 30 K the slope is roughly constant and $\kappa(T)$ can be approximated by a power law. We thus empirically fit the T2SL thermal conductivity with the local power-law expression $\kappa(T) = \kappa_0 (T_0/T)^s$, where $s$ is the power-law exponent, $T_0$ is the baseline temperature of interest, and $\kappa_0$ is the thermal conductivity at that temperature. Solving Eq. 6 under this local power-law assumption, the exact solution for the temperature profile in the active T2SL region with the same boundary conditions becomes

$$T(x) = T_0 \left[ 1 + (s + 1) \frac{\Delta T(x)}{T_0} \right]^{1/(s+1)},$$

where $\Delta T(x)$ is the same expression as in Eq. 7 and $s$ is the power-law exponent. In real devices, the change in temperature $\Delta T(x)$ will normally not exceed the absolute base temperature $T_0$, so this expression can be expanded for small $\Delta T(x)/T_0 < 1$

$$T(x) \approx T_0 + \frac{1}{2} s \frac{\Delta T^2(x)}{T_0}.$$  

The first two terms describe the thermal distribution for constant baseline thermal conductivity $\kappa_0$, and the third term accounts for the local power-law assumption, proportional to the exponent $s$. Note that the position of maximum temperature does not change between Eqs. 7 and 9, nor does the thermal derivative boundary condition at $x = 0$.

The typical power density dissipated in PDs is 10 kW/cm$^2$ to 250 kW/cm$^2$, and the threshold power density in ICLs is 0.3 kW/cm$^2$ to 2 kW/cm$^2$ when pulsed and 1 kW/cm$^2$ to 5 kW/cm$^2$ in continuous-wave operation. The dissipated power will be even larger when the device is operated at high output powers. We used a power density of 18 kW/cm$^2$ to simulate the thermal distribution in the active layer, as shown in Fig. 3. The maximum temperature is about a factor of 1.5 greater than the substrate absolute temperature $T_0$. When the exponent is positive, the peak temperature is reduced; for example, $s \approx 1$ for $T_0$ below 30 K. When the exponent is negative, the peak temperature is

Fig. 3. Calculated temperature profile in the active region normalized to the cold-sink substrate temperature $T_0$ with a typical power dissipation in a T2SL LED. The power dissipated is $P = 18$ kW/cm$^2$ and $\kappa_0 = 6$ W/mK is chosen. The power-law exponent $s = 0$ approximates the behavior in the intermediate temperature range $T_0 = 50$ K to 100 K whereas the $s = -1/2$ negative exponent is appropriate to higher temperatures $T_0 = 150$ K to 300 K and $s = 1$ to lower temperatures $T_0 = 13$ K to 30 K.
increased; for example, $s \approx -1/2$ for $T_0$ above 150 K. The power-law approximation to the thermal conductivity is developed further in Ref. 26.

Since other T2SL thermal conductivities have not been measured or published, this result can be used for qualitative estimates of other T2SLs. InAs/AlSb has a larger atomic mass mismatch resulting in larger acoustic phonon velocity mismatch at the interface than InAs/GaSb. Therefore, this superlattice, which is often used as the cladding layer in ICLs, should have an even lower thermal conductivity than this T2SL, which makes the power-law correction even more important under large heat loads.

The local power-law exponent $s$ in the neighborhood of an operating temperature $T_0$ can be determined as follows from the same empirical fit parameters as for Eq. 3:

$$s(T_0) = \left. \frac{d \log \kappa}{d \log T} \right|_{T_0} = -2B \log \left( \frac{T_0}{T_m} \right) + 3C \left[ \log \left( \frac{T_0}{T_m} \right) \right]^2. \quad (10)$$

We remark that these materials have been proposed as promising cryogenic thermoelectrics because below 20 K the thermal conductivity observed here is quite low, of order 1 W/m K, and because high Seebeck coefficients up to 2 mV/K for the hole band and 300 μV/K for the electron band at 4 K. We thus conclude that careful thermal modeling with the knowledge of the thermal conductivity reported here can improve T2SL device performance for a range of applications.

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