

Thermal Conductivity Reduction in GaAs–AlAs Distributed Bragg Reflectors

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Abstract—Self-heating of vertical-cavity laser diodes is strongly affected by the thermal conductivity of the distributed Bragg reflectors (DBR's). Binary GaAs–AlAs DBR's are expected to be good heat conductors, but investigations of GaAs–AlAs superlattices indicate strong interface scattering of phonons. For the first time, we present direct thermal conductivity measurements of separated GaAs–AlAs DBR's with a quarter-wave layer thickness of more than 100 nm (tuned to 1.55- μm wavelength). Using an ac calorimetric method and finite element analysis, we measure about 50% thermal conductivity reduction compared to the average bulk value. GaAs–AlAs DBR's for shorter wavelengths are expected to show an even lower thermal conductivity.

Index Terms—Semiconductor device thermal factors, semiconductor films, semiconductor materials measurement, temperature measurement.

SEMICONDUCTOR distributed Bragg reflectors (DBR's) are employed in various photonic devices, e.g., in vertical-cavity surface-emitting lasers (VCSEL's). Depending on the refractive index difference, about 20–40 pairs of alternating epitaxial materials are used to obtain vertical reflectivities above 99%. The layer thicknesses are one quarter of the photon wavelength resulting in a total DBR thickness of several microns. In the AlGaAs material system, combination of the binaries GaAs and AlAs gives the highest reflectivity, but GaAs–AlGaAs stacks are often used to reduce the vertical electrical resistance. Such DBR's have recently been utilized in wafer-fused long-wavelength VCSEL's emitting at 1.3- or 1.55- μm wavelength which are very sensitive to internal heating [1], [2]. Thermal resistance and self-heating of VCSEL's strongly depend on the DBR's thermal conductivity [3]. Due to alloy scattering of phonons, the thermal conductivity in ternary AlGaAs is up to one order of magnitude smaller than in the binary bulk material [4]. Therefore, binary DBR's are preferred at the n-doped bottom side of the VCSEL to allow for optimum heat flux to the stage.

However, the measured self-heating of VCSEL's is considerably higher than expected from bulk thermal conductivity data of GaAs (0.44 W/cm·K) and AlAs (0.91 W/cm·K) [5],

[6]. A possible cause for this phenomenon is the scattering of phonons at the DBR interfaces. In typical DBR's, heat conduction is mainly due to phonon diffusion. The phonon mean free path can be limited by several scattering mechanisms. Simple kinetic gas theory describes the thermal conductivity $\kappa = C_v v l / 3$ as a function of heat capacity C_v per volume, average phonon velocity v , and phonon mean free path l . Using bulk data of GaAs and AlAs [4], this equation allows for a rough estimation of $l = 10$ – 100 nm depending on the phonon velocity. It is reasonable to assume a considerable reduction of the thermal conductivity by interface scattering as long as the DBR layer thickness is on the order of the phonon mean free path. Measurements on GaAs–AlAs superlattices (SL's) with up to 50-nm layer thickness result in a thermal conductivity that is less than 45% of the average bulk value $\kappa_p = 0.68$ W/cm·K [7]. These numbers are for the thermal conductivity parallel to the interfaces. Vertical heat flux was not considered in [7] but the effect of interface scattering might be even larger. Recently, GaAs–AlAs SL's with 70-nm layer thickness have been investigated and 60% of the average bulk thermal conductivity is measured in a parallel direction [8].

For the first time, we present thermal conductivity measurements on GaAs–AlAs DBR's with layer thicknesses above 100 nm. The DBR was grown by molecular beam epitaxy at the University of California at Santa Barbara with a layer thickness of 115 nm (GaAs) and 134 nm (AlAs) to be employed in wafer-fused 1.55- μm VCSEL's [2]. These DBR's are 10^{18} cm^{-3} silicon doped and have a 20-nm linear interface grading with 5×10^{18} cm^{-3} pulse doping to reduce the electrical resistance. After growth of 28 DBR pairs, our 1.4×1.0 cm^2 sample was mounted DBR-down on thermally insulating epoxy and the GaAs substrate was removed by spray-etching.

The measurement is based on the ac calorimetric method [9] that was also employed in [7], [8]. Utilizing an ac heat source, this method generates plane temperature waves inside thin films and it uses the spatial decay of the wave amplitude $\hat{T}(x)$ to determine the thermal diffusivity D_p parallel to the surface. The thermal conductivity is obtained from $\kappa_p = D_p C_v$. The measurement setup is displayed in Fig. 1. Heat is provided by the halogen lamp (1) that illuminates part of the sample (2). The mechanical chopper (3) generates the heat source frequency f of about 7 Hz. A 10-cm-wide mask (4) shadows part of the sample and the heat wave travels parallel to the long axis. A metallic clamp serves as heat sink at the shadowed end of the sample. The mask is driven by a micrometer to change the distance between the heated part of the sample and the position of the thermocouple

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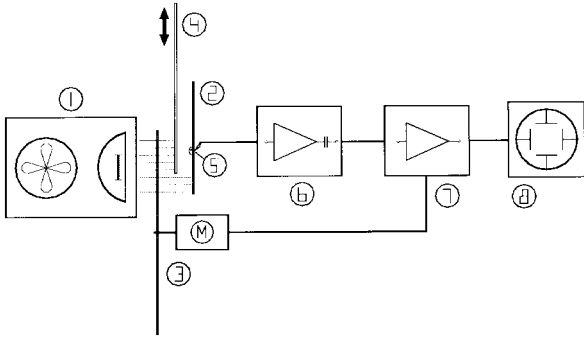


Fig. 1. Experimental setup (see text).

(5). We use a highly sensitive chromel alumel thermocouple OMEGA CHAL-002. The ac temperature signal goes from the thermocouple through a noninverting pre-amplifier (6) to the log-in amplifier (7) to filter the heat modulation frequency. The light chopper (3) provides the reference signal to tune in the log-in amplifier. A storage oscilloscope (8) is used to determine the ac temperature. The maximum temperature rise in the sample is less than 10 K.

To analyze the measurement and to obtain the thermal conductivity, two-dimensional thermal simulation is employed using a multipurpose finite-element code [10]. This numerical method avoids experimental restrictions that are connected with the analytical method used in [7]–[9]. The finite-element code solves the transient heat transfer equation

$$C_v \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \kappa_p \frac{\partial T}{\partial x} - \frac{\partial}{\partial y} \kappa_v \frac{\partial T}{\partial y} = q(x, y, t)$$

to obtain the two-dimensional temperature distribution $T(x, y, t)$ that is generated by the oscillating heat power density $q = q_o \times (1 + \sin(2\pi ft))$ within the region illuminated (a stepwise linear function $q(t)$ is used numerically). Heat conduction through the epoxy is found to be negligible as well as heat transfer to the air. Average bulk values are used for the heat capacity $C_v = 1.88 \text{ W}\cdot\text{s}/\text{cm}^3\text{K}$ of the DBR. Considering the difference in DBR layer thicknesses, AlAs and GaAs bulk thermal conductivities give an average of $\kappa_p = 0.69 \text{ W}/\text{cm}\cdot\text{K}$ in the parallel direction and averaging the bulk thermal resistivities κ^{-1} results in $\kappa_v = 0.61 \text{ W}/\text{cm}\cdot\text{K}$ in the vertical direction. Our thin-film measurement is hardly affected by κ_v . The DBR thermal conductivity is varied in the simulation to find agreement with the measured temperature $T(x, t)$ along the surface of the sample. Fig. 2 shows the time dependence of the solution $T(x_o, t)$ at a fixed distance $x_o = 2 \text{ mm}$ from the heated region. The time-dependent calculation starts with a steady-state solution to quickly reach equilibrium of the background temperature after about 15 ac periods (1.5 s). The amplitude $\hat{T}(x)$ of the temperature oscillation as a function of the distance x is then used to determine the thermal conductivity κ_p of the DBR.

The dots in Fig. 3 show the measured ac peak temperature $\hat{T}(x)$. To verify the method, 400- μm -thick GaAs with $5 \times 10^{18} \text{ cm}^{-3}$ silicon doping is used as first sample. The simulation (solid line) gives an isotropic thermal conductivity $\kappa_{\text{GaAs}} = 0.40 \text{ W}/\text{cm}\cdot\text{K}$ ($C_v = 1.97 \text{ W}\cdot\text{s}/\text{cm}^3\text{K}$). Due to the relatively high doping, this result is near the lower end of

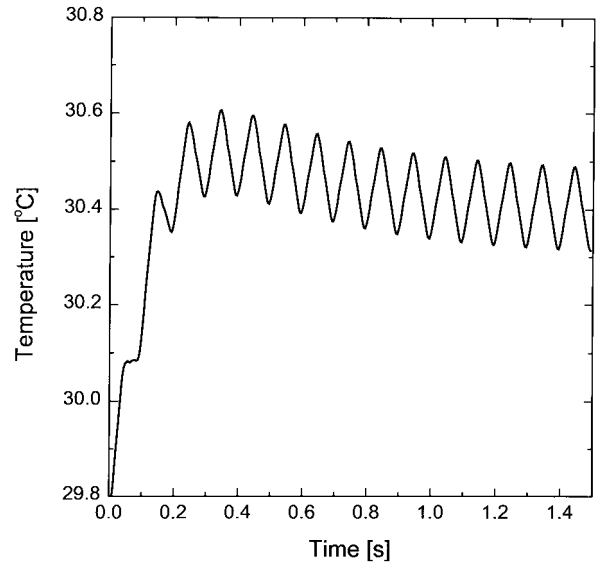


Fig. 2. Simulated time-dependence of the DBR surface temperature $T(x_o, t)$ at $x_o = 2\text{-mm}$ distance from the heated region ($f = 10 \text{ Hz}$).

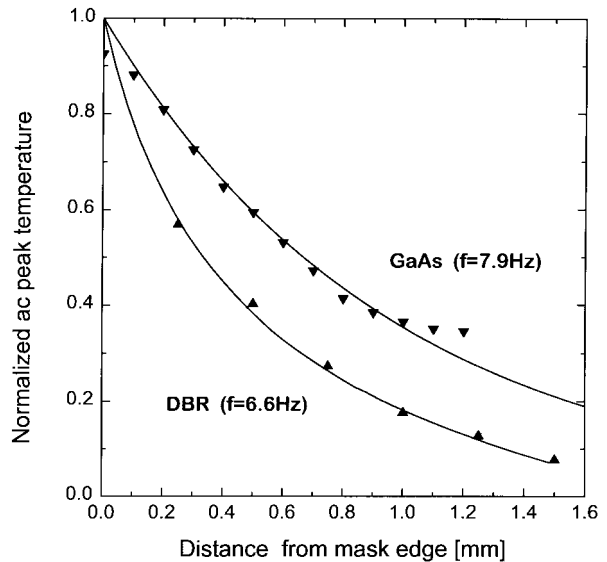


Fig. 3. Peak ac temperature \hat{T} at sample surface versus distance x from heated region.

the range 0.37–0.57 $\text{W}/\text{cm}\cdot\text{K}$ reported for GaAs [4]. At both ends of the GaAs curve, the measurement deviates from the simulation. This is caused by light diffraction at the edge of the mask (low x) or by noise (high x). The lower curve in Fig. 3 shows the results for the DBR film. The simulation gives the best fit for $\kappa_p = 0.35 \text{ W}/\text{cm}\cdot\text{K}$. Considering the measurement error, $\pm 0.05 \text{ W}/\text{cm}\cdot\text{K}$ accuracy is estimated. The result is slightly smaller than expected from extrapolations of superlattice (SL) measurements with lower layer thickness (Fig. 4). The additional thermal conductivity reduction can be attributed to higher doping and compositional grading of the DBR interfaces, which are typical for GaAs–AlAs DBR's to reduce the electrical resistance. On the other hand, our result is larger than expected from the self-heating of double-fused

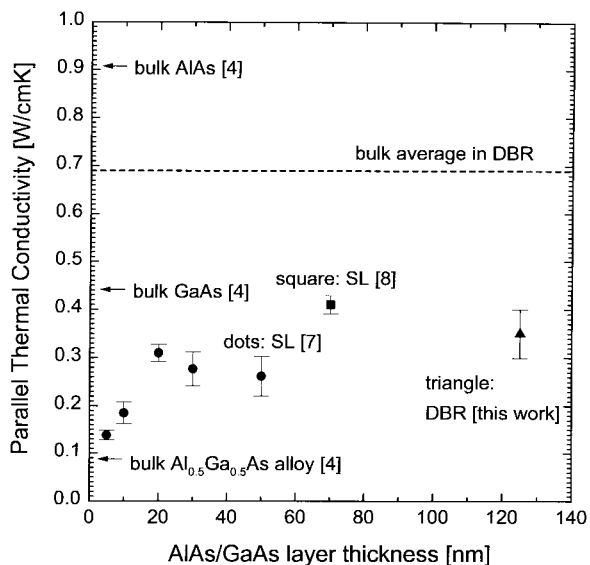


Fig. 4. Comparison of AlAs–GaAs thermal conductivity results.

1.55- μm VCSEL's because of the additional thermal resistance of the InP–GaAs fused interface [5].

The measured limitation of the parallel thermal conductivity κ_p restricts lateral heat spreading within binary bottom DBR's of VCSEL's which has an essential effect on the active region heating. In the vertical direction, the thermal conductivity κ_v across the DBR interfaces is assumed to be even smaller than in the parallel direction but it is hard to measure. Analysis of VCSEL self-heating indicates a ratio of $\kappa_v/\kappa_p = 0.80$ [6] which is slightly smaller than expected from binary bulk data (0.88). Direct measurements on entire VCSEL resonators including AlGaAs layers give a ratio of only 0.38 and substantially smaller values κ_p and κ_v due to the strong alloy scattering of phonons in ternary material [11].

In summary, GaAs–AlAs DBR's of 1.55- μm VCSEL's are shown to exhibit a thermal conductivity parallel to the

interface of 0.35 ± 0.05 W/cm·K, which is only half the average bulk value. This reduction is attributed to phonon scattering at the interface that is enhanced by interface grading and high doping. At shorter VCSEL wavelength, the thermal conductivity reduction is expected to be even stronger.

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