Thermal conductance measurements of a silicon nitride membrane at low temperatures

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Abstract

Silicon nitride membranes are used for thermal isolation in various devices, such as bolometric millimetre-wave detectors and lattice microrefrigerators. We have measured the thermal conductance of a 1.5μm thick silicon nitride membrane, between 0.1 and 0.3 K. At these temperatures, thermal transport in such thin films is believed to be dominated by phonon surface scattering, and not by bulk behaviour. We compare our results with theory, as well as experiments using films with different thicknesses.

Keywords: Thermal conduction; Thin films; Cryogenic instrumentation

The thermal conductance of silicon nitride membranes is important in various ultra-low temperature applications [1]. At sufficiently low temperatures, the phonon mean free path becomes larger than the membrane. The thermal conductance is then dominated not by bulk scattering, but by scattering from the surfaces. The conductance no longer scales with sample size, and it is not meaningful to calculate the thermal *conductivity*, which would vary with the sample dimensions.

Our experiments were carried out on a square silicon nitride membrane grown by low pressure chemical vapour deposition, with thickness 1.5 μm and sides 12.25mm long. Centred on the membrane was a 11mm$\times$11mm gold isothermal platform, on top of which was a layer of silicon, with two NTD germanium resistors attached using epoxy. Their temperature variation was given by

$$R(T) = R_0 exp\left(\sqrt{T_0/T}\right), \qquad (1)$$

with R_0 = 56.5Ω and 85.0Ω, and T_0 = 26.8K and 25.5K. Electrical contact was made using niobium-titanium superconducting wires, with negligable calculated thermal conductivity compared with the silicon nitride.

The sample was mounted on the stage of an adiabatic demagnetisation refrigerator, and contained inside a radiation shield maintained at 1.5K. For stage temperatures between 100 and 300mK, the current through one of the resistors was ramped, heating the isothermal platform, while a small bias current applied

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to the other one enabled it to be used as a thermometer.

A large thermal resistance was apparant between the resistors and the isothermal platform, which we ascribe to electron-phonon decoupling within the germanium. The temperature variation of this thermal resistance was approximately $T^{5.2}$, and the conductance per unit volume at 100mK was $110\mathrm{WK}^{-1}\mathrm{m}^{-3}$, consistent with values reported for NTD germanium [2].

Despite this resistance being much larger than that due to the silicon nitride, the small bias power to the thermometer caused a relatively small (and calculable) temperature lift from the isothermal platform, and the silicon nitride conductivity could still be determined to reasonable accuracy. However, relatively large temperature differences across the membrane were required (e.g. $>$5mK at 100mK). A variation in conductivity across the membrane, $G = G_0 T^{\beta}$, was assumed, with a single value for β fitting all stage temperatures.

To calculate theoretical predictions for our results, we approximate our membrane to four slabs, of cross-sectional area $1.5\mu\mathrm{m}\times 11\mathrm{mm}$, with the thermal gradient over 'length' l=1.25mm. Using a phonon radiative transfer model, the thermal conductivity can be written as

$$G = 4\sigma A T^3 \xi, \qquad (2)$$

where $\sigma = 15.7\mathrm{mWcm}^2\mathrm{K}^4$ for silicon nitride, and A is the cross-sectional area [3]. The dependence on l is contained in ξ, which varies depending on the nature of the surface scattering. Upper (ξ=1) and lower (ξ=ξ_c) limits occur for wholly specular and wholly diffuse scattering, respectively. However, the latter limit has not been seen in membranes [3]. We obtain ξ_c using an expression appropriate for large cross-sectional aspect ratios [4].

From figure 1 it can be seen that our results fall significantly below the specular reflection limit. This is in contrast to measurements using similar membranes with thickness between 0.85μm and 1.02μm, for which the specular limit was reached at 100mK, except in the case of deliberate surface contamination [3]. It is possible that our sample suffered some unintentional contamination.

The thermal conductance at 100mK is (9.5 $\pm$ 1) $\times$ 10^{-9} WK^{-1}. The temperature dependence fits a powerlaw with β = 2.05 $\pm$ 0.1, compared with 1.98 measured in membranes 200nm thick [5], and 2-2.5 in the membranes used in reference [3].

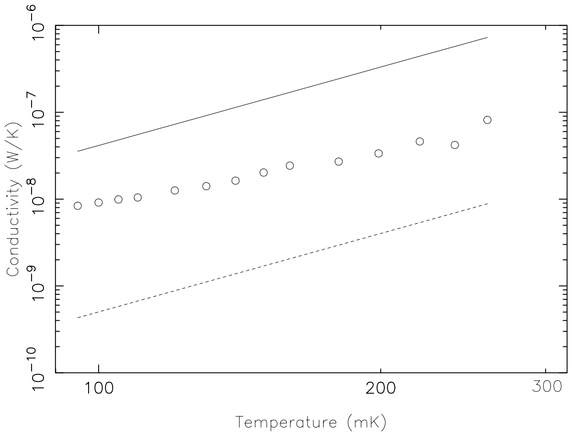

Fig. 1. Measured thermal conductivity as a function of cryostat stage temperature. The solid and dashed lines show the specular and diffuse scattering limits respectively.

In conclusion, our results agree with the phonon surface scattering picture. We thank Tom Kenny at Stanford University for providing us with the silicon nitride membrane.

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