Phonon transport in suspended silicon nitride membranes at low temperatures

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Abstract. We have studied experimentally the nature of phonon transport in 750 nm and 200 nm thick free-standing silicon nitride (SiNₓ) membranes over a temperature range of 0.1-1K. Measurements were performed by using a radially symmetric DC heater and several normal metal-insulator-superconductor (NIS) tunnel junction thermometers to detect the phonon temperature \( T_p \) at several different distances from the heater. Our data indicates that phonon transport is three dimensional in both membranes, and mostly ballistic at the low temperature range of our experiment. At temperatures above 0.5 K there are indications of a transition to a more diffusive regime.

1. Introduction
For many low temperature applications such as commonly used bolometric radiation detectors [1], knowledge of the thermal properties of the surroundings is essential for optimizing the operation of the device. Many of these devices are placed on top of suspended silicon nitride (SiNₓ) membranes, because they enable thermal insulation, are quite durable and have processing techniques that are straightforward and well known. However, heat transport properties of SiNₓ membranes at low temperatures are not yet well established.

The temperature dependence of the power flow between two arbitrary points with temperatures \( T_1 \) and \( T_0 \) has the form \( P = K (T_1^n - T_0^n) \), where \( T_1 > T_0 \). Here the prefactor \( K \) and the exponent \( n \) both depend on the nature of the phonon transport (i.e. ballistic or diffusive), sample geometry and phonon dimensionality [2, 3, 4]. In the case of diffusive transport, \( n \) and \( K \) depend further on the dominant scattering mechanism [5]. In this paper, we discuss our results in terms of the power flow \( P \) instead of thermal conductance or thermal conductivity, so that results for varying definitions of thermal conductance (differential or non-differential) can be calculated from our data. Previously, Leivo et al. [6] reported that the temperature dependence of the power flow in 200 nm thick SiNₓ membranes below 1 K was close to \( P \propto T^3 \), and analysed their results in terms of a diffusive model. On the other hand, Holmes et al. [7] measured phonon transport in several \( \approx 1 \) \( \mu \)m thick SiNₓ membranes with temperature dependence varying between \( P \propto T^{3.1-3.4} \) and absolute value approaching the fully ballistic limit around \( T = 0.1 \) K. In addition, they showed that the surface conditions have a significant influence on the thermal conductance. Furthemore, Hoevers et al. [8] also observed mostly ballistic transport in 1 \( \mu \)m thick SiNₓ membranes at \( T \approx 0.1 \) K, with a temperature dependence \( P \propto T^{3.6} \) close to the 3D ballistic limit \( P \propto T^4 \) [9].
In this paper, we show experimental results on phonon thermal transport measurements performed on 200 nm and 750 nm thick suspended SiN membranes at temperatures between 0.1 - 1 K. The novelty features in our sample design are: (i) We use a radially symmetric design of the heater and thermometers to minimize geometry dependent effects in ballistic transport, and (ii) we measure phonon temperature at several distances from the heater to obtain better statistics for the data and to study distance dependent effects.

2. Sample fabrication

Figure 1 shows a schematic of the samples studied. Suspended membranes (size \( \sim 550 \times 550 \ \mu m^2 \)) were fabricated by etching double-side nitridized (100) silicon wafers anisotropically in an aqueous KOH solution. Nitridization was performed by an LPCVD process with parameters optimized for low-stress SiN. Metallic structures (heater and thermometers) were fabricated on the suspended membranes by electron beam lithography and multiangle shadow mask evaporation techniques. Two samples with different membrane thicknesses (750 nm and 200 nm), but with identical metallic structures were fabricated. The measured rms surface roughness perpendicular to the membrane plane is about 1-2 nm.

A circular copper wire heater of width \( \sim 200 \ \text{nm} \) and thickness 30 nm is located at the center of the membrane. The radius of the heater is 7 \( \mu m \) and the length of the perimeter 42.5 \( \mu m \). At both ends of the heater Cu wire, superconducting Nb leads (width \( \sim 1 \ \mu m \), thickness 40 nm) contact it directly (NS junctions). Six superconductor-normal metal-superconductor (SINIS) tunnel junction thermometers [10] are located around the heater at different distances from the center of the circular heater, measuring the phonon temperature \( T_p \). The normal metal parts (Cu) of the tunnel junctions are also radially symmetric with respect to the center, with a constant length of the arc of 8 \( \mu m \) for each thermometer. The thermometer leads are superconducting Al (width \( \sim 300 \ \text{nm} \), thickness \( \sim 15 \ \text{nm} \)), and the tunnel junction barriers are formed by thermally oxidizing the Al leads after evaporation.

### Figure 1.

(Color online) A schematic of the samples and the measuring circuit. Light green area is a suspended silicon nitride membrane, red lines are normal metal Cu, light gray thermally oxidized Al for SINIS tunnel junctions and dark gray Nb for heater leads. Phonon thermometers are at the following distances from the origin: SINIS1 15 \( \mu m \), SINIS2 38.3 \( \mu m \), SINIS2 61.3 \( \mu m \), SINIS4 97.9 \( \mu m \), SINIS5 156.5 \( \mu m \), SINIS6 250.2 \( \mu m \). Thickness of the copper wire is 30 nm and width \( \sim 200 \ \text{nm} \). Input power of the heater is determined by a four probe configuration. SINIS6 shows the measuring circuit for all the tunnel junction thermometers.

3. Results and discussion

In the measurement, we ramp Joule heat into the heater wire and measure (i) the input current and voltage to obtain the input Joule power, \( P = IV \), and (ii) the temperature at every thermometer location as a function of the input power. The superconducting Nb heater leads provide excellent electrical, but poor thermal conductance due to Andreev reflection. Thus,
heat diffusion into the leads is negligible, and all the input power is dissipated uniformly in the wire. This causes radially symmetric phonon emission power from the heater. The SINIS tunnel junction thermometers are current biased \((I_b \sim 5-500 \text{pA})\) to give the local \(T_p\) from the measured voltage across the junction. A more detailed description of tunnel junction thermometry can be found in Refs. [11, 12].

Figure 2 shows the measured input heating power \(P\) versus local phonon temperature \(T_p\) in log-log scale for each of the phonon thermometers SINIS 1-6 for the 750 nm [Fig. 2 (a)], and 200 nm [Fig. 2 (b)] thick membrane samples. In both samples, phonon temperature decreases with distance from the heater, as expected. Comparing the two membranes, we also clearly see that that thinner 200 nm membrane heats up more, and has therefore a lower thermal conductance. The saturation of the temperature at low heating powers (more clearly visible for the 750 nm membrane) is due to external noise heating [11], and does not reflect the phonon temperature caused by the heater.

![Figure 2](image)

**Figure 2.** (Color online) Measured input power \(P\) versus phonon temperature \(T_p\) for the 750 nm thick membrane sample (a) and for 200 nm thick membrane sample (b). In both graphs from bottom to top, Gray dot: SINIS1, Magenta dot: SINIS2, Black dot: SINIS3, Light gray dot: SINIS4, Blue open circle: SINIS5 and Cyan open circle: SINIS6. Black, dashed lines are guides for the eye to study the temperature dependence of the heat flow.

The temperature dependence of the heat flow is studied with dashed lines in both figures 2 (a) and (b). On the 750 nm thick membrane [Fig. 2 (a)] all phonon thermometers follow approximately the same temperature dependence, \(P \sim T^4\) in a temperature range 0.2-0.6 K. This indicates that phonons are three dimensional, consistent with our previous measurements [12]. In addition, scattering mechanisms that have a strongly temperature dependent phonon mean free path can be ruled out, hinting that we are in the surface limited regime. At higher temperatures above 0.6 K, the phonon temperatures start to increase faster, and temperature dependence seems to approach \(P \sim T^3\). This may indicate a transition to more bulk limited scattering regime, such as scattering from two-level systems [13]. On the 200 nm thick membrane [in Fig. 2 (b)] the results are qualitatively similar. However, at the furthest thermometers the exponent looks a bit higher than 4 at low temperatures.

To put out results into perspective, we should compare them to previous work and theoretical limits. In Fig. 3 we have plotted our result from the thermometer SINIS4 on the 200 nm membrane (about 100 \(\mu\)m away from heater), and compare it to the result by Leivo et al. [6], who had the same thickness membrane and same distance in their experiment. A very good agreement is achieved at temperatures above 0.5 K, but significant deviations develop at lower temperatures. This disagreement is not yet understood. In addition, we have plotted two theoretical limits: The fully ballistic (specular) limit [9], and the fully diffusive surface scattering
Figure 3. (Color online) P versus \( T_p \) for the phonon thermometer SINIS4 on the top of the 200nm thick membrane. Gray solid line: Results by Leivo et al. [6]. Upper dashed line: theoretical ballistic limit, Lower dashed line: Casimir limit. (Casimir) limit [5]. We can see that our data is clearly closer to the ballistic limit, but starts to deviate from it more strongly at \( T > 0.5 \) K.

4. Conclusions
We have studied phonon transport in 750 nm and 200 nm thick suspended silicon nitride membranes. Our data indicates that phonon transport is three dimensional in both membranes, and mostly ballistic at the low temperature range of the experiment. At temperatures above 0.5 K there are indications of a transition to a more diffusive regime. The temperature dependence and strength of phonon transport are in agreement with previous results at the high temperature range above 0.5 K, but more clear indications of mostly ballistic limit was obtained at below 0.5 K.

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