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研究課題名（和文）Engineering directional heat flow in semiconductor nanostructures

研究課題名（英文）Engineering directional heat flow in semiconductor nanostructures

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研究成果の概要（和文）：マクロスケールでの古典的な熱拡散とは異なり、ナノスケールの半導体においては、フォノンの弾道性が顕著になる。本研究では、さまざまな形状のナノワイヤを用いた熱拡散測定を比較することで、ナノワイヤ自体の熱伝導率を直接的に測定した。これにより、シリコンで弾道的フォノン輸送が生じる温度とナノワイヤ長さの範囲が得られ、ナノワイヤにおけるフォノン輸送の指向性が調べられるようになった。フォノンの弾道的性質は、4 Kで、ナノワイヤ長さが400 nmのとき最も強く見られ、より高温でより長いナノワイヤでは徐々に弱くなることを発見した。

研究成果の学術的意義や社会的意義
These results showed that silicon is can exhibit strong ballistic heat conduction only at low temperatures. Hence for real-world applications, such as heat dissipation in microelectronics, we should search for materials with longer phonon mean free path, such as SiC, BN, or BAs.

研究成果の概要（英文）：Unlike classical heat diffusion at the macroscale, nanoscale heat conduction in semiconductors can happen “ballistically”, i.e. without energy dissipation, because individual phonons can travel in straight lines for hundreds of nanometers without resistance. In the past few years, such ballistic heat conduction has been demonstrated in semiconductor nanowires and membranes. However, these demonstrations were rather indirect because they were based on measurements of overall thermal conductivity of the entire nanostructures.
Here, I measured the billistic heat conduction in nanowires more directly, comparing the heat dissipation through the nanowires of different shapes. These experiments yielded the length and temperature ranges of ballistic heat conduction silicon and enabled probing directionality of phonon transport in nanowires. I found that ballisticiy is strongest in shortest nanowires (400 nm) and at 4 K and gradually weakens at higher temperatures and longer nanowires.

研究分野：Phononics

キーワード：phonons　thermal conductivity　thermal transport　nanowires

１．研究開始当初の背景

Research on heat conduction in silicon nanostructures becomes increasingly important due to never ending miniaturization of microelectronic devices and growing demand for thermoelectric nanostructures. In nanostructures, classical diffusion from hot to cold can no longer adequately describe heat conduction because individual phonons can travel in straight lines without energy dissipation for hundreds of nanometers.

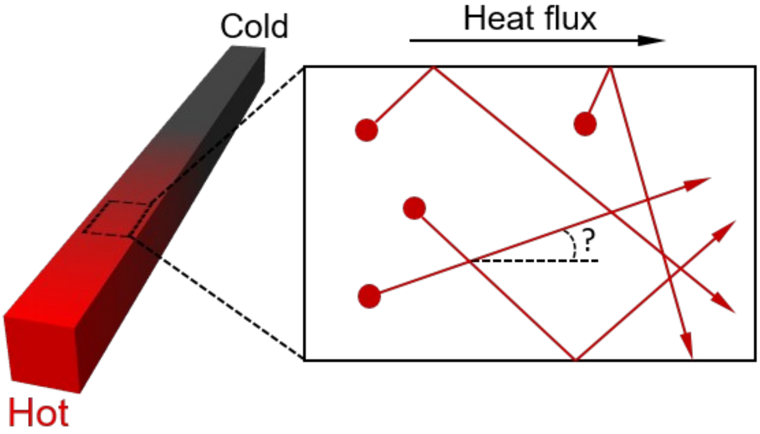

Figure 1. Schematic of phonon transport in a nanowire. Phonons travelling in a nanowire can have various angles and directions, which are unknown.

Such point-to-point propagation of phonons causes ballistic heat conduction (i.e. conduction without resistance), which has recently been demonstrated in various nanostructures. However, the length and temperature ranges of ballistic heat conduction in silicon remain unknown. Moreover, the ballisticity is the characteristic of the heat conduction in general, whereas the fundamental interest lies in the behavior of individual phonons. In this porhect, I also wanted to observe experimentally in which directions phonons propagate in conventional nanostructures, such as nanowires, nanobeams, and membranes. For example, Figure 1 illustrates that phonons in a nanowire can have many possible trajectories; currently, even overall directionality of phonon motion is unknown. Particularly, it is unknown whether phonon trajectories have preferential direction or directions are purely isotropic, like in diffusive picture of heat conduction.

２．研究の目的

Thus, the main goals of this research is to develop a method to directly measure the ballistic heat conduction and directionality of phonon transport in nanostructures. Previous studies did not observe signs of ballistic heat conduction directly, but measured overall thermal conductivity as a function of structure size, and thus concluded on the presence of ballistic transport. Here, I aim to observe ballistic heat conduction directly by measuring directions of phonon propagation, and thus to understand heat conduction at qualitatively new level – the level of phonon trajectories.

３．研究の方法

Thus, I plan to develop a method to measure directionality of phonons at different points of a nanowire and thus to probe anisotropy of the phonon directions. In general, in the two-year period I fabricated several sets of samples, measured them using time-domain thermoreflectance (TDTR) technique, and performed Monte-Carlo simulations to compare to experimental results. Figure 2 shows a schematic of a typical sample I used. The sample consists of a suspended island, with a metal pad on the top, connected to the wafer by nanowires, which are the object of the measurements. Using the TDTR setup, schematically shown in Figure 2,

I could measure how quickly heat, created by each pulse of the pump laser, dissipates from the metal pad through the nanowires. Unlike many conventional techniques for thermal measurements, my micro thermoreflectance setup is time-resolved. This gives me access to dynamics of phonons in time, which is principally different from conventional steady-state measurements.

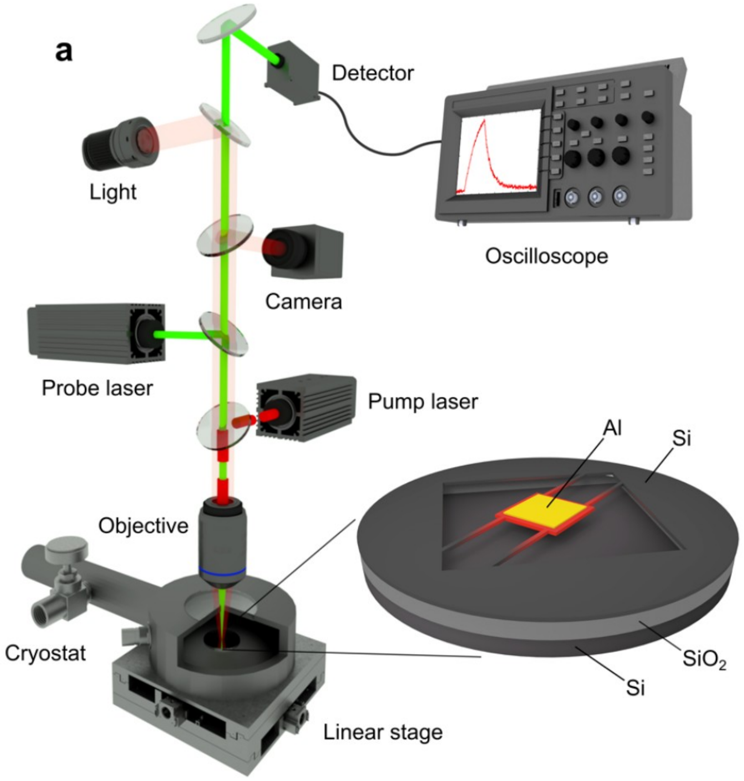

Figure 2. Schematics of a typical sample and the TDTR setup for thermal transport measurements.

４．研究成果

First, measuring nanowires of different shapes and sizes, I show that the ballisticity is the strongest in short nanowires at low temperatures (Figure 3) but weakens as the nanowire length or temperature is increased [1]. Yet, even at room temperature, quasi-ballistic heat conduction remains visible in short nanowires.

However, measuring directional phonon transport I could barely detect any directionality. There results supported by Monte Carlo simulations show that the quasi-ballistic phonon motion in nanowires is essentially the Lévy walk like transport with short flights between the boundaries and long ballistic leaps along the nanowire axis [1].

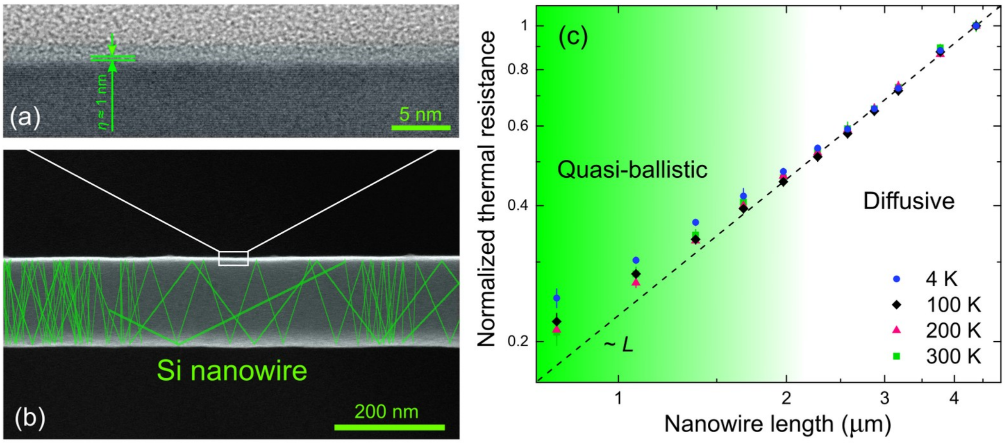

Figure 3. (a) TEM image shows low surface roughness. (b) SEM image of silicon nanowire with simulated phonon paths. (c) Thermal resistance of short nanowires deviates from a linear diffusive trend indicating quasi-ballistic behavior.

Next, I experimentally probed ballistic thermal transport at distances of 400 – 800 nm and temperatures of 4 – 250 K [2]. Measuring thermal properties of straight and serpentine Si nanowires, I found that at 4 K heat conduction is quasi-ballistic with stronger ballisticity at shorter length scales (Figure 4). At higher temperatures, I observed how quasi-ballistic heat conduction gradually turned into diffusive at temperatures above 150 K.

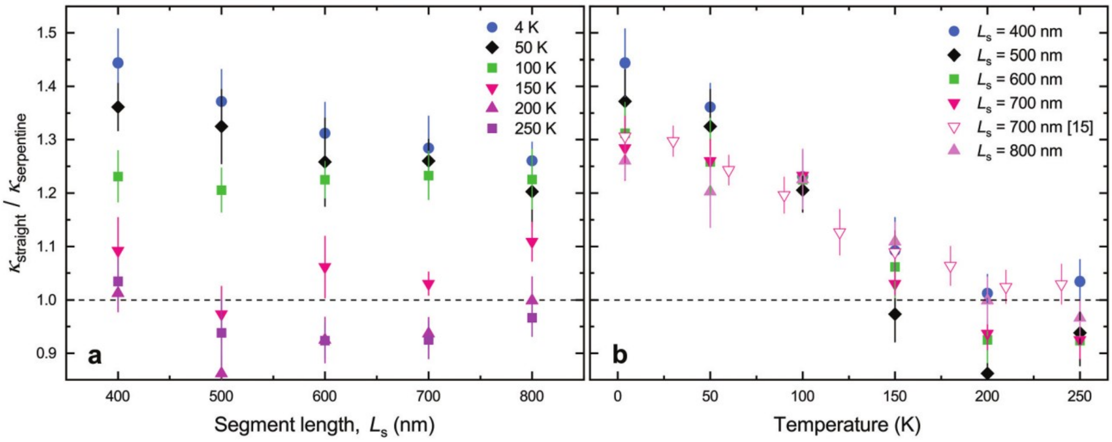

Figure 4. Transition from quasi-ballistic to diffusive heat conduction. The relative thermal conductivity of pairs of NWs (a) with different segment lengths and (b) at different and temperatures.

My Monte Carlo simulations showed how this transition is driven by different scattering processes and linked to the surface roughness and the temperature [2].

Summarizing, these results demonstrate the length and temperature limits of quasi-ballistic heat conduction in Si nanostructures, knowledge of which is essential for thermal management in microelectronics.

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〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　1件）

１．著者名 Roman Anufriev , Sergei Gluchko, Sebastian Volz, and Masahiro Nomura	４．巻 12
２．論文標題 Quasi-Ballistic Heat Conduction due to Levy Phonon Flights in Silicon Nanowires	５．発行年 2018年
３．雑誌名 ACS Nano	６．最初と最後の頁 11928
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acsnano.8b07597	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Roman Anufriev and Masahiro Nomura	４．巻 9
２．論文標題 Coherent Thermal Conduction in Silicon Nanowires with Periodic Wings	５．発行年 2019年
３．雑誌名 Nanomaterials	６．最初と最後の頁 142
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/nano9020142	査読の有無 有
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１．著者名 Roman Anufriev , Sergei Gluchko, Sebastian Volz, and Masahiro Nomura	４．巻 11
２．論文標題 Probing ballistic thermal conduction in segmented silicon nanowires	５．発行年 2019年
３．雑誌名 Nanoscale	６．最初と最後の頁 13407
掲載論文のDOI（デジタルオブジェクト識別子） 10.1039/C9NR03863A	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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４．発表年
2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

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