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研究課題名（英文）Thermal phonon spectroscopy of phononic crystals by using a MEMS thermometer

研究代表者
張　亜（Zhang, Ya）

東京農工大学・工学（系）研究科（研究院）・准教授

研究者番号：８０７７９６３７

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研究成果の概要（和文）：本研究では、新規なMEMS温度計を用いてフォノニック結晶（PnC）におけるフォノン輸送に関する研究を行った。MEMS梁の上に二次元PnCを作製し、梁の熱減衰を測定によって、梁構造の熱伝導の変化を計算した。PnCに穴の直径が約300 nmまで減少すると、熱伝導は顕著な低下を示し、フォノン効果が材料の熱伝導率を低減させたことを確認した。
更に、MEMS梁に時間制御した二重フェムト秒光パルスを照射し、2つの光パルス間の時間遅延の関数としてMEMS梁の温度上昇を測定した。梁にコヒーレントフォノン輸送による干渉パターンを観測した。フーリエ変換によって、MEMS梁を通してフォノンスペクトルの観測は成功した。

研究成果の学術的意義や社会的意義
本研究は、超高速フォノン分光法を実施するための強力な方法を提供し、半導体マイクロ/ナノ構造における熱輸送プロセスに対する理解を大きく深化させるものである。さらに、その知見が、マイクロ/ナノ材料の熱特性における多くの研究に広く応用できるため、基礎研究と社会の両方に大きなインパクトを与える。従って、本研究に基づき、更なる研究の開拓が期待できる。将来的には、フォノンの波動性による熱輸送の制御を可能にし、半導体デバイスに対する理想的な熱制御につながり、エネルギー効率の高い社会の構築にも役立つと期待できる。

研究成果の概要（英文）：We have utilized a novel MEMS thermometer as a powerful tool for studying the thermal transport in phononic crystals(PnC). We fabricated two-dimensional PnCs on GaAs MEMS beam. By measuring the thermal decay time of the beams with and without PnCs, we obtained the change in thermal conductance of MEMS beams by PnCs. When the hole diameters in PnCs were decreased to ~300 nm, the PnCs gave notably larger drops in thermal conductance than the theoretical expection, suggesting that the phononic effect changed the thermal conductivity of the GaAs material.
Furthermore, we sent two light pulses from a femtosecond laser with a modulated time delay to heat up the MEMS beam, and we measured its temperature rise as a function of the time delay between two pulses, which gives a phonon interference pattern owing to the coherent phonon transport in the GaAs beam. By performing Fourier transform, we determined the phonon spectrum through the GaAs beam.

研究分野：半導体マイクロ・ナノ構造

キーワード：フォノン分光法　フォノニック結晶　熱輸送　MEMS　半導体　マイクロ/ナノ構造

１．研究開始当初の背景

(1) Sustainable energy systems become more and more important since the fossil fuel is running up. The thermoelectric devices, which directly convert waste heat into useful electricity, are very important for building an energy-efficient society. Since the thermoelectric coefficient is inversely proportional to the thermal conductance of materials, reducing the thermal conductance is very crucial for improving the efficiency of energy harvesting by thermoelectric devices.

(2) It has been known that phonon is responsible for the transmission of heat in solids. Acoustic phonons carry thermal energy along the temperature gradient direction from the high temperature area to low temperature area, forming the basic heat transport process. It is therefore very crucial to study the phonon spectroscopy for investigating the thermal properties of materials. In particular, we are interested in the phonon prorogations in artificial phononic structures, i.e. phononic crystals.

２．研究の目的

This research aims at utilizing a novel MEMS thermometer as a powerful tool for studying the thermal transport in two-dimensional phononic crystals.

(1) We integrate two-dimensional phononic crystals on the MEMS beam, and study how the thermal conductance of the MEMS beam is modulated by phononic crystals.

(2) We aim at developing a novel phonon spectroscopy platform by using the MEMS thermometer, to measure the phonon spectrum of semiconductor micro/nano structures.

３．研究の方法

(1) We fabricated two-dimensional phononic crystals on GaAs MEMS beam by using nano-fabrication technology. By measuring the thermal decay times of the beam with and without phononic crystals, we obtained the change in thermal conductance of MEMS beam by phononic crystals.

(2) Two light pulses from a femtosecond laser with a modulated time delay were sent to heat up the MEMS beam, and then we measured the temperature rise on the beam as a function of the time delay between two light pulses, which gives a phonon interference pattern owing to the coherent phonon transport in the GaAs beam. By performing Fourier Transform for the interference pattern, we determined the phonon spectrum through the GaAs beam.

４．研究成果

(1) Improve the sensitivity and operation speed of MEMS thermometer

To measure the ultra-small phonon transport signal, a thermometer with high sensitivity, large dynamic range and fast operation speed is very crucial. In this research, we first focused on improving our MEMS thermometer to fulfill the requirements of phonon transport research.

In the MEMS thermometer we previously developed[1], the limitation of maximum input power(typically 0.5~1 mW) mainly comes from the buckling effect. When a small amount of heat is applied to the MEMS beam, reduction in resonance frequency is observed. As the heating power is further increased, however, the resonance frequency levels off and starts to increase, which originates from the buckling of the beam. Therefore, the input power must be limited to a small power range to keep a good linearity of the MEMS thermometer.

Here, we intentionally introduced a preloaded internal compressing stress to induce the buckling before the input of heat. we have fabricated a buckled MEMS beam resonator by using a strained $In_xGa_{1-x}As$ ($x \approx 0.001$) beam structure on a GaAs substrate. Figure 1(a) shows a comparison between GaAs MEMS thermometer and InGaAs MEMS thermometer by SEM images. As seen in the figure, GaAs beam is flat, whereas InGaAs beam shows notable buckling. Figure 1(b) plots the normalized frequency shifts of the InGaAs and GaAs resonators. We have found that the frequency responsivity of the InGaAs beam sample is about 3 times higher than that of the GaAs beam sample, and has a better linearity, demonstrating that the introduction of buckling is useful for achieving higher thermal sensitivity and higher dynamic range for the MEMS thermometers.

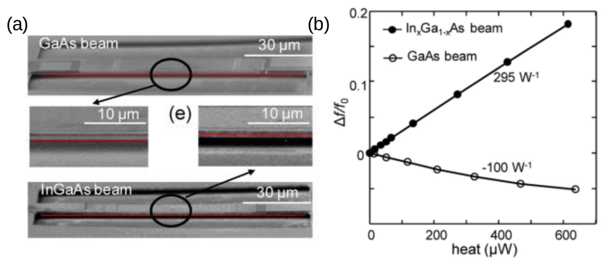

Figure 1. (a) Comparison between GaAs MEMS thermometer and InGaAs MEMS thermometer by SEM images. InGaAs MEMS beam shows notable buckling. (b) The measured frequency shift of GaAs and InGaAs MEMS thermometers.

Furthermore, we have applied a frequency-modulation (FM) detection scheme using a phase-locked loop (PLL) and achieved an operation speed as high as several kHz, which is not limited by the resonator’s Q-factor but by the thermal time constant of the MEMS beam. By using the FM detection, our MEMS bolometer is ~100 times faster than that of the conventional room-temperature thermal detectors, such as VOx bolometers and pyroelectric detectors.

(2) Reduced thermal conductance by phononic crystal

We have fabricated two-dimensional(2D) phononic crystal (PnC) structures on GaAs MEMS beam resonators to modulate their thermal properties. The holes were formed by using reactive ion etching with Cl_2 gas and a rf power of 200 W at 50 °C for 80 s. The suspended beam structure was formed by selectively etching the sacrificial layer with diluted hydrofluoric acid. Figure 2(a) shows an optical microscope image of a fabricated MEMS beam resonator with a 2D PnC structure of a hole diameter d = 500 nm and the neck size (the distance between neighboring holes) n = 500 nm. The inset of Fig. 2(a) shows a blow-up of an SEM image of the PnC structure, showing that the fabricated hole array is homogeneous.

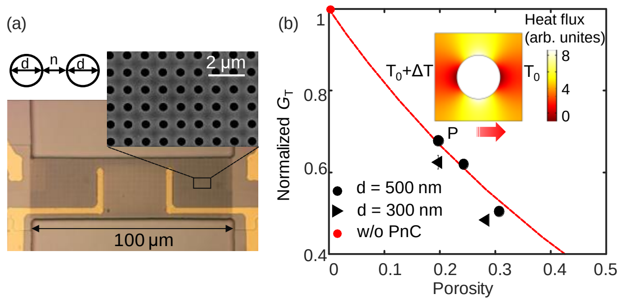

Figure 2. (a) Optical microscope image of a fabricated MEMS beam resonator with a 2D PnC structure. (b) The normalized thermal conductance of the PnC MEMS beams with various diameter(*d*) and neck size(*n*).

Figure 2(b) shows the measured thermal conductance of the GaAs beam with PnCs as a function of the porosity, which is defined by the ratio of the material volume removed from the beam to the volume of the beam before fabricating PnC structures. The thermal conductance is normalized by a reference beam without PnC. As seen, the PnC structures fabricated in this work have a porosity of 0.2-0.3 and the thermal conductance is reduced by 40%~50% in our samples. In particular, when the hole diameters were decreased to 300 nm, the PnCs gave notably larger drops in the thermal conductance than the theoretical calculation (red dashed line in Fig. 2(b)), suggesting that the phononic effect from PnC has changed the thermal conductivity of the material.

(3) Phonon spectroscopy by using the MEMS thermometer

We sent two ultra-short light pulses from a Ti-sapphire femtosecond laser (pulse width ~100fs, central wavelength 800 nm) to the MEMS thermometer. The generated phonons by the laser pulses propagate through the GaAs beam, and interfere with each other. We measure the phonon interference signal as the temperature rise on the beam by measuring the frequency shift of the MEMS resonator. If coherent phonon transfers exist in the beam, the temperature rise will have a dependence on the time delay between two light pulses, showing a phonon interference pattern. By performing a Fourier transform for the interference signal, we obtained the phononic spectrum of the heat transport process.

Figure 3(a) shows the observed phonon interference pattern, and Fig. 3(b) shows the spectrum calculated by performing Fourier transform for the interference data. As seen, the spectrum has a cutting frequency at about 100 GHz and a long tail lasted to about 400 GHz, which proves that our phonon spectroscopy method is able to measure the phonon spectrum in the sub-terahertz (THz) range. We have found that the cutting frequency is mainly limited by an envelope function determined by the size of the laser heating spot. Here we used a metal slit of a width 100 ~200 nm to generate a small heating spot. The bandwidth of the envelop function can be furthermore improved by using surface plasmonic structure to give an ultra-small (~10 nm) laser heating spot. Therefore, our method has the potential to measure the phonon propagations in the terahertz (10^{12}) range.

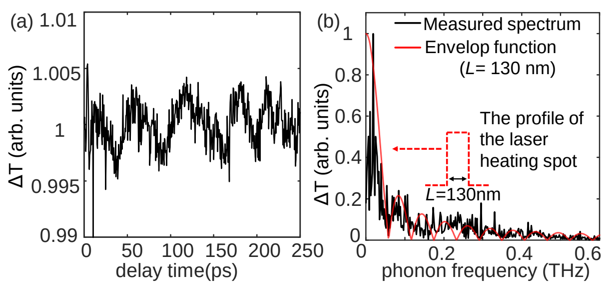

Figure 3. (a) The temperature rise of MEMS thermometer measured as a function of delay time between two laser pulses (interference pattern). (b) The heat transport spectrum, and the envelop function calculated by the width of the irradiation slit.

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５．主な発表論文等

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〔その他〕
ホームページ　http://web.tuat.ac.jp/~zhang/researche.html

６．研究組織
研究協力者
研究協力者氏名：平川　一彦
ローマ字氏名：Kazuhiko　Hirakawa

研究協力者氏名：野村　政宏
ローマ字氏名：Masahiro　Nomura