Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp319-320

Near-field cavity optomechanics in an InP/InAs heterostructured nanowire with a silica optical microsphere cavity

Motoki Asano, Guoqiang Zhang, Takehiko Tawara, Hiroshi Yamaguchi, and Hajime Okamoto
NTT Basic Research Laboratories.
Morinosato Wakamiya, Atsugi-shi, Kanagawa 3-1, Japan
Phone: +81-46-240-3825 E-mail: motoki.asano.gm@hco.ntt.co.jp

Abstract

A compound semiconductor nanowire is a strong candidate for hybridizing photonic, electronic, and mechanical degrees of freedom towards novel quantum hybrid interfaces. Although introducing the "cavity optomechancis" framework to such a nanowire makes it possible to precisely detect and control its mechanical motion, the size difference between a typical optical cavity and nanowire is an obstacle to achieving sufficient optomechanical coupling between them. Here, we demonstrate near-field cavity optomechanical coupling to an InP/InAs heterostructured nanowire with a whispering-gallery-mode optical microsphere cavity. The near-field optomechanical coupling allows us to high-sensitivity read out the thermal motion in two orthogonalized modes as well as to control the mechanical responses via optical gradient force. Applying the near-field approach to a compound semiconductor nanowire with a quantum structure would pave the way to quantum metrology and information processing with hybrid systems.

1. Introduction

Compound semiconductor nanowires have been a strong candidate for hybrid quantum interfaces when it includes quantum structures. This is because such internal quantum structures enable us to tune optical resonance wavelengths from visible to telecom regions [1,2], which is advantageous in achieving wavelength-tunable quantum state of light for metrology and communications. Moreover, such a tunable internal quantum structure can couple excitonic states to mechanical vibration (i.e., phonons) via strain [3,4]. Thus, hybridizing the photons, phonons, and electrons in compound semiconductor nanowires could make it possible to develop novel hybrid quantum interfaces. However, it is technically difficult to precisely read out and control its tiny motion due to their small electrical capacity, low optical absorbance, and reflectivity in the nanowires.

Integrating nanowires with an optical cavity might be a straightforward approach to enhance the displacement sensitivity and controllability thanks to a cavity-enhanced interaction between the mechanical motion and strongly confined cavity photons. However, optomechanical coupling of a cavity to nanowires has scarcely been attempted [5] because the optical cavity integration is quite challenging due to the size difference between them.

Here, we report a demonstration of near-field cavity optomechanical coupling between a movable whispering-gallery-mode (WGM) microsphere cavity and a compound semiconductor nanowire. An optical evanescent field in the movable microsphere cavity allows us to induce optomechanical coupling by tuning the gap between the sphere and nanowire. Therefore, high-sensitivity displacement measurement is available via balanced homodyne interferometry. Moreover, functional control of mechanical responses (e.g. frequency and linewidth, and vibration direction) is achieved via cavity-enhanced optical gradient force. Combining cavity optomechanical coupling and optoelectric properties in heterostructured nanowires would open the way to novel hybrid quantum interfaces.

2. Experimental results

Device and setup

InP/InAs heterostructured nanowires (length of 14 μm; diameter of 500 nm) were grown on an InP (111)B substrate in a metal organic vapor phase epitaxy system via the self-catalyzed vapor-liquid-solid approach. The internal InP/InAs layer structure was tuned so that the optical absorption appears at around 1200 nm. A 1550-nm probe light was used to purely evaluate optomechanical coupling without any excitonic effects from the nanowire. A microsphere (diameter: 40 μm) was fabricated from a silica optical fiber by the standard discharge technique. The Q factor of the WGM was determined to be 1.8×10^5 from the optical transmission via a tapered fiber contacting on the microsphere. For optomechanical coupling, the nanowire substrate was loaded on a three-axis nanopositioner, and the nanowire approached the microsphere in a vacuum environment at room temperature [see Fig. 1(a)]. Note that we define the x-axis along a radial direction of WGM.

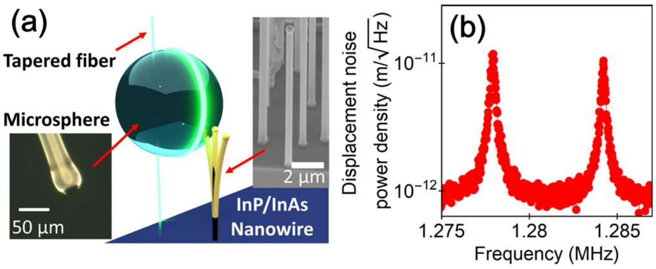

Fig.1 (a) Conceptual illustration of near-field optomechanical coupling between a microsphere and nanowire along with an optical microscope image and a scanning electron microscope image, respectively. (b) Displacement noise power density of thermal motion in the two orthogonalized modes observed via balanced homodyne interferometry.

Displacement measurement in thermal motion

Adjusting the nanowire position so that the optical evanescent field overlaps to the mechanical motion of nanowire leads to linear optomechanical coupling, which allows us to read out mechanical displacement as an optical phase shift. By constructing a fiber-based balanced homodyne interferometer with a 15-uW optical probe and 3-mW local oscillator, we were able to observe the thermal motion of two orthogonalized modes in the nanowire at the frequencies of 1.278 and 1.284 MHz which are referred to as mode 1 and mode 2, respectively [see Fig. 1(b)]. The linewidths of mode 1 and mode 2 are 283 and 222 Hz, which correspond to the mechanical Q factors of 4.5×10^3 and 5.8×10^3, respectively. The linear optomechanical coupling coefficients defined as $g_{\mathrm{lin}} = x_{\mathrm{zpf}}\partial\omega/\partial q$ with a zero-point fluctuation x_{zpf}, cavity resonance frequency ω, and mechanical displacement q, were determined to be $2\pi \times 28.5$ and $2\pi \times 23.9$ Hz. These linear optomechanical coupling result in a noise floor level of 8.2×10^{-1} $\mathrm{m}/\sqrt{\mathrm{Hz}}$. Since this noise floor level corresponds to the level of thermal motion at 2.8 K, the current optomechanical coupling could be valid for resolving thermal motion in a liquid helium environment, where rich excitonic properties in compound semiconductor nanowire are observed [3,4]. Furthermore, optimizing taper-microsphere coupling by introducing an additional positioner can increase the optical Q factor to the order of 10^7, which could resolve the mechanical displacement at the standard quantum limit ($= 2.9 \times 10^{-15}$ $\mathrm{m}/\sqrt{\mathrm{Hz}}$) with an appropriate optical power. This ultrasensitive measurement would pave the way to precise manipulation of mechanical motion in nanowires up to the quantum-limited regime [6].

Control of mechanical responses

In addition to precise detection of mechanical displacement via linear optomechanical coupling, strongly confined cavity photons exert an optical gradient force that leads to a modulation of the spring constant and energy dissipation rate of mechanical modes (i.e., frequency and linewidth). Thus, adjusting the gap between the microsphere and nanowire enables us to control the mechanical frequency and linewidth via optomechanical coupling. Figure 2(a) shows the two orthogonalized modes with respect to the gap with an optical probe power of 3.0 μW. Apparently, the mechanical frequencies and linewidths were exponentially shifted and broadened, respectively, with a decreasing gap because of the exponential profile of optical evanescent field. The amount of shift differed between the two modes around the small gap region (x<100 nm), in which the shift of mode 1 gained, whereas that of mode 2 converged. This is because the vibration directions of the two modes were rotated due to the intermodal coupling via optical evanescent fields [see Fig. 2(b)]. This rotation of the vibration directions was evaluated by the angle between the direction of mode 1 and the x-axis, which was experimentally extracted from the power spectral density of the two modes [7]. Although the initial angle (i.e., no gradient force) was almost 45 degrees, the angle at the smallest gap reached 18.9 degrees. This indicates that the cavity-enhanced optical gradient force rotates the vibration direction so that the lower-frequency mode (mode 1) tends to be parallel to the radial direction of the WGM (i.e., the x-axis). Introducing a control laser independent of the probe light for balanced homodyne interferometry would further functionalize these control operations, including the optical spring effect with finite detuning [6]. In addition to the optical control of the linear mechanical responses, we observed the optical control of Duffing nonlinear responses [10].

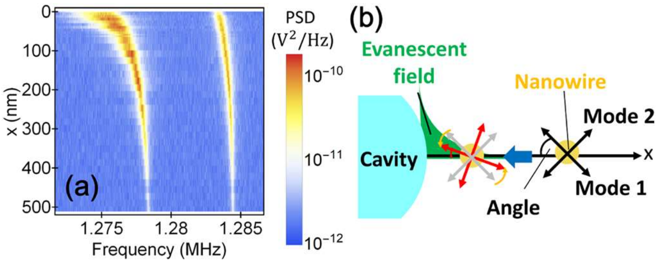

Fig.2 (a) Power spectral density of thermal motion in the two orthogonalized modes with respect to the gap between the microsphere and nanowire. (b) Schematic of rotation of vibration directions in a nanowire via optical gradient force.

3. Conclusion

In conclusion, we demonstrated near-field optomechanical coupling between a silica microsphere and an InP/InAs heterostructured nanowire. Both high-sensitivity displacement measurement and functional control of mechanical motion were achieved thanks to the movable microsphere's good accessibility to the nanowire. This near-field approach makes it possible to extend the cavity optomechanics to various types of nanowire devices such as nanowire field effect transistors and quantum dots [8,9]. Precisely detecting and controlling mechanical motion would open the way to hybrid quantum interfaces with photons, phonons, and various quantum states in compound semiconductor nanowires.

Acknowledgements

We thank Samer Houri and Ryuichi Ohta for their fruitful comments. This work was partly supported by JSPS KAKENHI (No. JP15H05869 and No. JP15K21727).

References

[1] D. Saxena *et al.*, *Nano lett.* **16**, 5080 (2016).
[2] G. Zhang *et al.*, *Sci. adv.* **5**, eaat8896 (2019).
[3] M. Montinaro *et al.*, *Nano lett.* **14**, 4454 (2014).
[4] M. Munsch *et al.*, *Nature commun.* **8**, 1 (2017).
[5] F. Fogliano *et al.*, arXiv:1904.01140 (2019).
[6] M. Aspelmeyer *et al.*, *Rev. of Mod. Phys.* **86**, 1391 (2014).
[7] N. Rossi *et al.*, *Nat. nanotech.* **12**, 150 (2017).
[8] A. Husain *et al.*, *Appl. Phys. Lett.* **83**, 1240 (2003).
[9] H. S. Solanki *et al.*, *Appl. Phys. Lett.* **99**, 213104 (2011).
[10] M. Asano *et al.*, arXiv:2006.16538 (2020).