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Experimental and Theoretical Study on SAW Resonances and Their Dispersion Relations in 1D Phononic Crystals
一次元フォノニック結晶における表面波共振と分散関係の実験的理論的研究

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1. Introduction

In recent years, because of the advances in fabrication technologies for nanostructures, miniaturization of devices is rapidly progressing. Among them, phononic crystals are intensively studied for creating new acoustic devices. Phononic crystals are periodic composite materials with lattice spacing comparable to the acoustic wavelength and can control acoustic waves with a specific wavelength through diffraction, scattering, and interference. Recent progress in the phononic crystals stimulated interests in ultrahigh-frequency surface acoustic waves (SAWs) propagating on periodic structures fabricated on solid surfaces. Periodicity often causes wave slowing and creates band gaps. In particular, laser-generated SAW resonances in a periodic nanostructure show high frequencies, so that new applications, such as ultrahigh-sensitive sensors, are expected. From this application standpoint, it is important to understand the oscillation property of SAWs both experimentally and theoretically.

In this work, we fabricate copper nanowires on silicon substrates using electron-beam lithography, and excite ultrahigh-frequency SAW resonances using picosecond ultrasonics. We then propose a new model for calculating dispersion relations of ultrahigh-frequency SAWs, where the rectangular nanowires are treated as periodic mass loading and periodic elastic strips with no volume. The dispersion relations show band gaps at the boundary and the center of the Brillouin zone (BZ). SAWs at the center of BZ (zero group velocity) indicate the sanding waves. Laser excitation of SAWs has proved to be a beneficial technique for the study of such zero-group-velocity modes. We use picosecond ultrasonics for the excitation and detection of SAWs on nanostructures consisting of a periodic array of copper nanowires on a (100) silicon substrate. By changing the wire spacing, we investigate SAW resonances, and compare them with the proposed theory.

2. Experiments

We use the pump-probe method for performing the mechanical spectroscopic measurement for the nanowire specimens. Thomsen

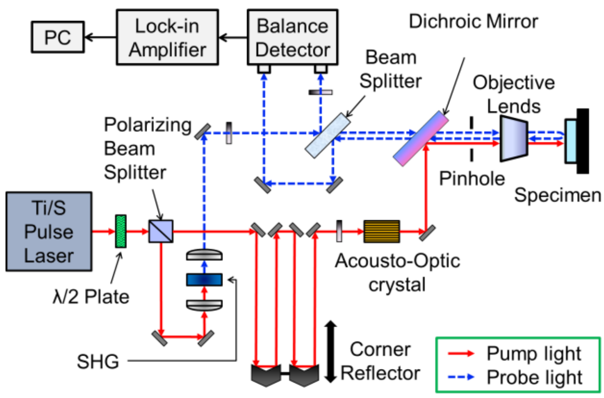

Fig. 1 Schematic of our optics. Solid line shows the pump light pulse (800 nm). Dashed line shows the probe light pulse (400 nm)

et al.[1)] detected high frequency coherent acoustic phonons using ultrafast pump-probe light pulses for the first time. Following their work, the picosecond ultrasonics was developed for the study of ultrahigh frequency acoustic properties of solids. We use a femtosecond pump light pulse to excite an ultrasound and a probe light pulse to detect it.

We originally developed the optics as shown in **Fig. 1**. We use a titanium-sapphire pulse laser (80 MHz, 800 nm, 140 fs) and divided the light pulse into pump and probe light pulses by a polarizing beam splitter (PBS). Their power ratio is adjusted by a $\lambda/2$ plate. The pump light is modulated at 100 kHz by an acousto-optic (AO) crystal, and the frequency of the probe light is doubled by a second harmonic generator (SHG) crystal. Both of them are perpendicularly incident on a specimen and we distinguish them by a dichroic mirror (DM), which reflects 800 nm wavelength light and transmits 400 nm wavelength light. Irradiation of the specimen with the pump light pulse (800 nm) excites coherent acoustic sources and generates vibrations related with SAW resonances on the substrate surface. They are detected by the time-delayed probe light pulse (400 nm) through the change in its reflectivity.

The specimens consist of copper nanowires on (100) silicon substrates using the electron-beam lithography technique. **Fig. 2(a)** shows the schematic of the nanowire specimen, and **Figs. 2(b)**

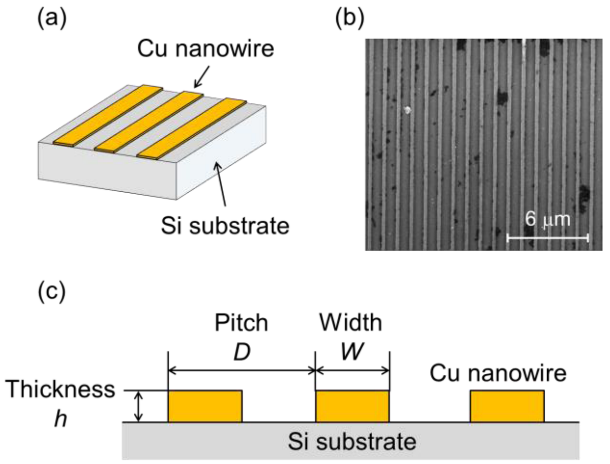

Fig. 2(a) Schematic of the nanowire specimen. (b) SEM image of the specimen. (c) Cross section image of the specimen.

and **(c)** show a scanning electron microscope image and the cross-section of the specimen, respectively. We prepared two kinds of specimens. First, (specimens I), the pitch D was varied between 600 and 1450 nm with fixed thickness (h=30 nm) and width (W=1000 nm). Second, (specimens II), the width W was varied between 100 and 440 nm with fixed thickness (h=30 nm) and pitch (D=1000 nm). All of them consist of 499 nanowires with 500 μm long.

3. Theoretical Model

Following the plane wave expansion method[2,3], SAWs are constructed as a superposition of partial plane waves in the substrate. Substituting the displacement equation into the boundary conditions at the surface yields the dispersion relations. The previous approach[3], taking into account the only mass loading effect, failed to explain our measurements. We then propose a new model, taking into account elastic properties as well. It leads to elastic restoring force like surface tension.

4. Results and Discussion

Fig. 3(a) shows an example of the time-resolved reflectivity change observed for a specimen on Si substrate with h=30 nm, W=300 nm and D=1000 nm. **Fig. 3(b)** shows its FFT spectrum, displaying peaks at 4, 7.5, and 10 GHz; they are identified to be SAW resonances. The irradiation of the specimen surface with the pump light pulse excites vibrations of about 50 nanowires at the same time, and they can be sources of SAWs. When the wavelength of the SAW is close to the pitch D of the nanowires, significant amplitude

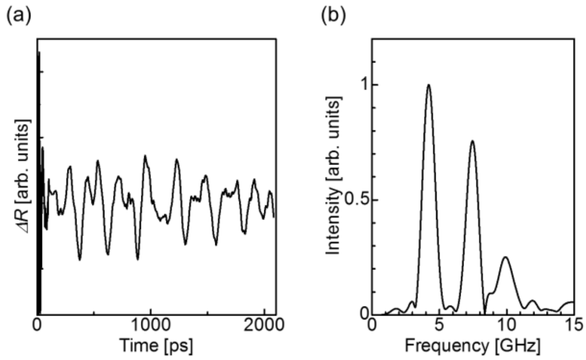

Fig. 3 (a) Time resolved reflectivity change observed for nanowires specimen, and (b) their FFT spectrum.

enhancement occurs. Thus, the frequencies of the SAW resonances are roughly estimated by $f_{SAW}=mv_{RW}/D$, where m is the resonance order number, and v_{RW} is the Rayleigh-wave velocity of silicon. Using v_{RW}=5000 m/s[4], we have f_{RW}=5 GHz for m=1. In the case that nanostructures are periodically deposited on the substrate, SAW propagating on the substrate is dispersive and observed SAW velocity is lower than theoretical value because of the periodic mass loading. Our measurements showed a band gap at a specific pitch, which is absent in the previous model. Our new model, however, reproduces the band gap.

5. Conclusion

We succeeded in observation of ultrahigh-frequency SAW resonances with a very small error (0.58%). In previous researches[5,6], nanowires are fabricated with lower acoustic-impedance materials than substrates, leading to less attenuation of SAW. However, in the SAW resonance biosensors, a high acoustic-impedance metallic material is fabricated on the substrates leading to the leak of the SAW energy into the substrates. Even in such a specimen, we can observe practical SAW resonances.

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