Surface-phonon Polaritons Appearing on the Surface of SiC and the Potential of Their Interaction with Surface-plasmon Polaritons

Y. Yamamoto[1], J. Miyata[1], N. Umemori[1], K. Kasahara[1], T. Yaji[1], N. Ozaki[2], N. Ikeda[3], and Y. Sugimoto[3]

1) Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan

2) Wakayama University, Sakaedani 930, Wakayama-city, Wakayama 640-8510, Japan

3) National Institute for Materials Science (NIMS), 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

Abstract

Circular slot antennas were formed in an array on the surface of SiC. Surface phonon polariton signals, caused by light and longitudinal-optical phonon coupling, were investigated by changing the distance between the neighboring antennas. The spectra varied with the change in the distance. It was possible that surface plasmon polaritons, in which electrons have a role, produced an effect on the spectral transformation.

1. Introduction

Optical antennas enhance the electric field inside the substrate on which they are mounted, and make it possible to increase the midinfrared intersubband absorption in quantum wells consisting of thin layers, and to realize high-performance mid-infrared detectors. So far, we have developed a technique for investigating electric-field distributions of optical antennas in the depth direction by means of atomic layer deposition (ALD) (1). There, circular slot antennas were formed on an ALD-made Al_2O_3/SiC substrate. Surface-phonon polariton (SPhP) signals originating from the SiC substrate (2) were used to gain an understanding of the enhanced electric field perpendicular to the substrate by varying the Al_2O_3 thicknesses experimentally. SPhPs are electromagnetic surface modes formed by the strong coupling of light and longitudinal-optical phonons in polar materials. However, when light interacts with a metal surface, it excites electrons, and produces surface-plasmon polariton (SPP) on the metal. The mixed plasmon-phonon surface modes in n-InSb was investigated using a modified attenuated total reflection method (3), and it is possible that electrons propagating on the surface of the metal interact with optical phonons existing on the surface of the underlying substrate via the long-range polar Fröhlich coupling (4). In this research, the potential of the SPhP-SPP interaction has been investigated by varying the distance between neighboring optical antennas in an array.

2. Fabrication of Circular Slot Antennas

Circular slot antennas were fabricated on a SiC substrate. Their patterns were made with electron-beam lithography. Then, Au (40 nm)/Ti (10 nm) were deposited on the substrate, followed by a lift-off technique that cut out circular openings in the metal sheet. One antenna array consisted of 10 x 10 elements, each having the same size. The diameter of the circles was 3 to 6 μm. The antennas were arranged in a triangle pattern. The distance of the adjacent antennas was varied: 9, 12, 17 μm. The reflection spectra were measured with a micro FTIR. The incident angle θ of the FTIR was 20 degrees, and the normalized reflectivity was obtained using the spectrum from Au.

3. Results and Discussion

To know whether SPPs were generated on the Au surface, FTIR measurements were performed while rotating the samples relative to the FTIR input light. The results for a device having a dimeter of 6 μm and a pitch of 9 μm are shown in Fig. 1. Input light was launched in the x direction, and the samples were rotated counterclockwise from the original position as shown in the inset of the figure. The reflection spectra changed due to the rotation of the sample. One can see that when the rotation angle is 30 degrees, a notable educed reflectivity appears at 1020 cm^{-1}, together with 979 cm^{-1} which appears at 0 degrees [Fig. 1 (b)]. The latter 979 cm^{-1} signal originated from the Fabry-Perot resonance of the circular antenna. The spectrum measured at 60 degrees should return to the 0-degree's spectrum due to a triangular symmetry, and the measured result was almost as was expected. The slight spectral difference between 0 and 60 degrees was probably due to the fact that the area that was occupied by the antennas was finite. SPP signals are produced at two interfaces: air/Au and SiC/Au, and the resonance conditions are given by

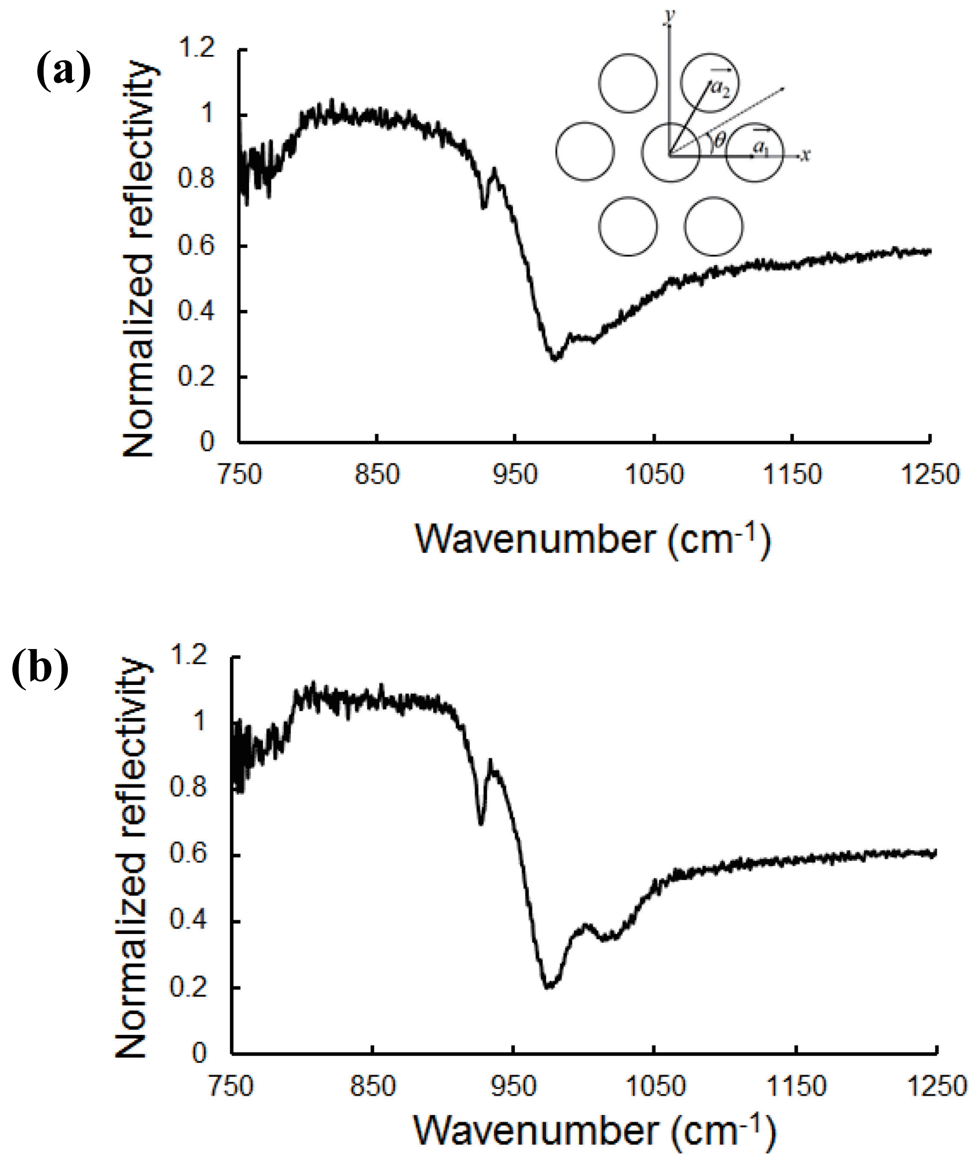

Fig. 1 Normalized reflectivity spectra for (a) θ = 0 , and (b) θ = 30 degrees. 10 x 10 array in a triangle pattern with each antenna having a diameter of 6 μm and a pitch of 9 μm.

$$\left|\overrightarrow{k_{spp}}\right| = \left|k_0 \sin\theta \overrightarrow{e_x} + m\overrightarrow{b_1} + n\overrightarrow{b_2}\right|, \tag{1}$$

where $\left|\overrightarrow{k_{spp}}\right| = \sqrt{\varepsilon_d \varepsilon_{Au} /(\varepsilon_d + \varepsilon_{Au})}$ (ε_d :permitivity of SiC or air), $\overrightarrow{e_x}$:unit vector in the x direction, $\overrightarrow{b_1}$ and $\overrightarrow{b_2}$:reciprocal vectors defined from $\overrightarrow{a_1}$ and $\overrightarrow{a_2}$, m and n : integer. A wood anomaly condition is achieved by replacing the left-hand term in Eq. (1) of. As the component nk_0 (n :refractive index of SiC) of the input light wavenumber parallel to the surface ($= k_0 \sin\theta$) wasn't negligible compared to the magnitude of the reciprocal vectors, the SPP resonance condition changed with sample rotation. The resonance conditions determined by Eq. (1) and that of the Wood anomaly differed little in our case, and it was found through calculation that the SPP modes (m, n) = (0, 1) and (0, -1) appearing at the Au-SiC interface affected the spectral change associated with the rotation.

Next, we measured the spectral dependence on pitch using the devices with the same diameter. Figure 2 shows the results obtained from the 6-μm diameter devices with three different pitches, p. The spectra around the SPhP signals were obviously different, and Fig. 3 shows the wavenumber of the dips in reflectivity for cases measured without inserting a

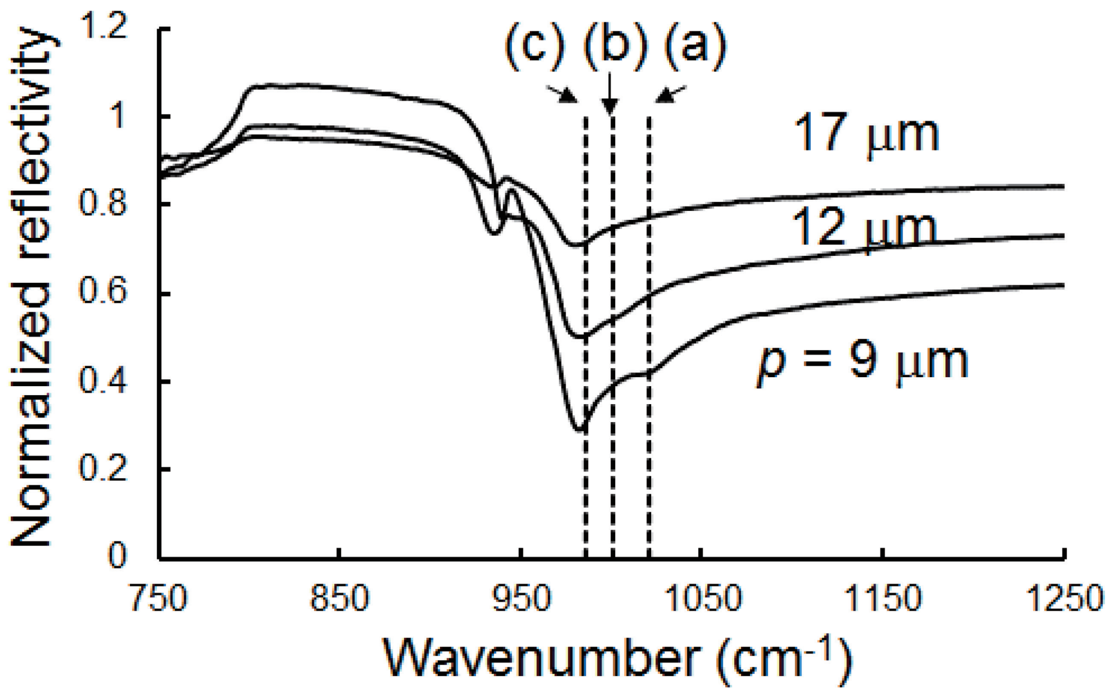

Fig. 2 Normalized reflectivity for 6-μm diameter devices with three different pitches. (a), (b), and (c) indicate the wavenumber calculated from the Wood anomaly condition between the Au-SiC interface for $(m, n) = (0, \pm 1)$ with p = 9, 12, and 17 μm, respectively.

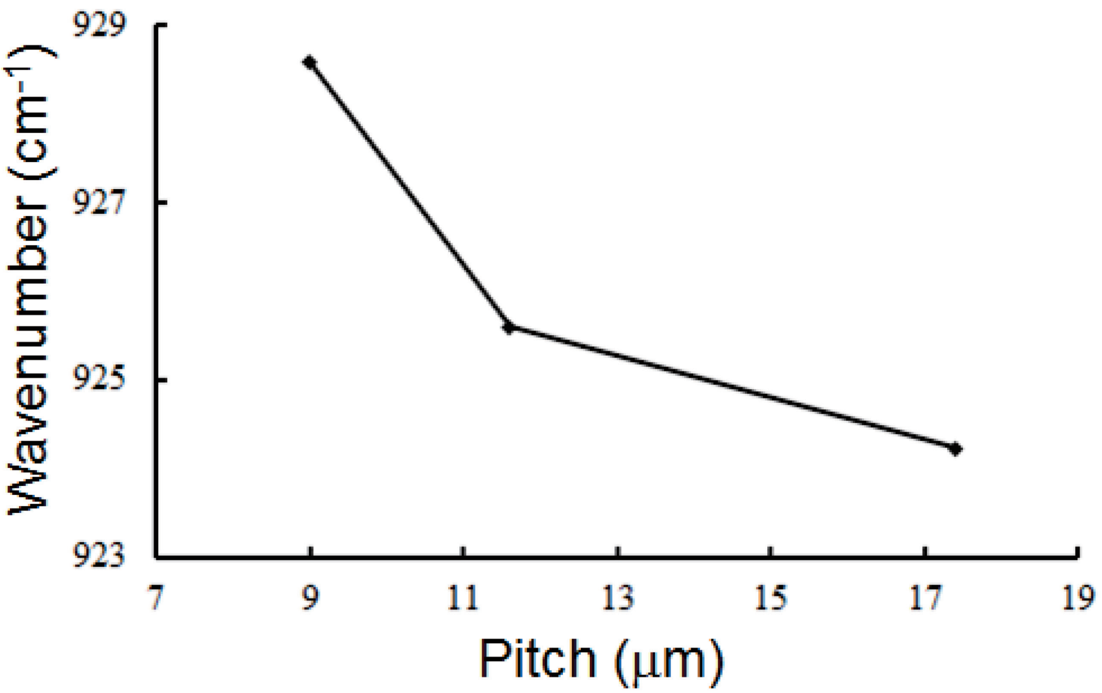

Fig. 3 Wavenumber of the reflectivity dips measured for three pitches without a polarizer.

polarizer for the input light. They decreased from 929 cm^{-1} to 924 cm^{-1} accompanied by increase in pitches. The lines (a), (b), and (c) in Fig. 2 are the wavenumber, calculated from the Wood anomaly condition between the Au-SiC interface for $(m, n) = (0, \pm 1)$ with $p = 9$, 12, and 17 μm, respectively. They were slightly situated higher than the Fabry-Perot resonance and SPhP signals. However, this mode approached as the distance was increased. It is noted that the Fabry-Perot resonance signals determined by the dimeter of the circular antennas did not change, and stayed at 979 cm^{-1}, regardless of spacing. Therefore, it was probable that the interaction between SPhPs and SPPs resulted in the observed spectral change.

4. Conclusions

SPhPs and SPPs have been observed and treated independently in past optical antenna-used experiments, but they should mutually affect each other. Fröhlich coupling occurs due to the electron-phonon interaction, and is the coulomb interaction in principle, causing a potential deformation. Superconductivity arises from electron-phonon interaction. Optical antennas can open the possibility of being applicable in the investigation of the ellectron-phonon interactions in a broad area without being limited to polar crystals.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 23560043, and Nano-Integration Foundry (NIMS) in "Nanotechnology Platform Project" operated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

(1) Y. Nishimura, T. Kawano, Y. Kunichika, K. Kasahara, T. Yaji, N. Ikeda, H. Oosato, H. Miyazaki, Y. Sugimoto, "Observation of the enhancement of electric fields normal to the surface using mid-infraed slot antennas and an atomic layer deposition technique", *Opt. Commun.*, **2015**, 349, 98.

(2) T. Wang, P. Li, B. Hauer, D.N. Chigrin, and T. Taubner, "Optical properties of single infrared resonant circular micro cavities for surface phonon polaritons", *Nano Lett.*, **2013**, 13, 5051.

(3) V.V. Bryxin, D.N. Mirlin and I.I. Reshinak, "Surface plasmon-phonon interaction in n-InSb", *Solid State Commun.*, **1972**, 11, 695-699.

(4) E. H. Hwang, R. Sensarma, and S.D. Sarma, "Plasmon-phonon coupling in graphene", *Phys. Rev.*, **2010**, B 82, 195406.