Electric Field Distribution Perpendicular to the Surface of Mid-infrared Antennas

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Abstract

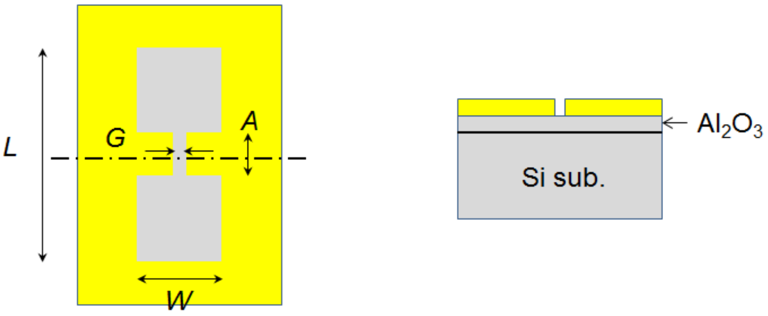
The electric field in the normal direction was experimentally investigated by using mid-infrared antennas that were formed on a thin Al_2O_3 layer/Si substrate. The Al_2O_3 layer could be as thin as a single nm-order employing the atomic layer deposition, and was varied from 2 nm to 50 nm. The field distribution was estimated by observing the reflectivity change. It was found that the electric field decreased rapidly until a 6 nm depth from the antenna plane, and that the degree of attenuation became relaxed in the deeper region.

I. INTRODUCTION

Optical antennas have opened the way for investigating micro areas, and thus, it is vital to understand the electric field distribution around the antenna. Observation of the reflection spectra with the use of a microscopic Fourier transform infrared (FTIR) spectrometer makes it possible to identify the enhancement of the electric field of an optical antenna. Measurements are the results caused by the increased electric field adjacent to the antenna in both horizontal and vertical directions. If one could use, for example, scattering near-field microscopy (s-SNOM) [1], local information on the field enhancement on a plane would be available. However, such information obtained in a certain position includes data perpendicular to the plane. In the surface-enhanced infrared absorption spectroscopy (SEIRA), the scattering from objects might significantly contribute to the extinction cross section, as it scales with the fourth power of the electric field [1], [2]. To elucidate more about this mechanism, it is important to know the actual field distribution normal to the antenna plane. However, few studies have been carried out on this matter. Towards this end, we applied the atomic layer deposition (ALD) to make a substrate on which antennas were formed [3]. In this paper, we measured the FTIR spectra of those devices and discussed the field localization in the normal direction. For this purpose, we varied the thickness of ALD-fabricated Al_2O_3 until it was as thick as 50 nm.

II. FABRICATION OF DUMBBELL-SHAPED SLOT ANTENNAS

Figure 1 shows the antenna structure. A thin Al_2O_3 layer was deposited on a Si substrate with the use of ALD. The ALD allowed the growth of the layer with the thickness being



(a) (b)

Fig. 1 Dumbbell-shaped antenna structure. (a) Plane view and (b) cross-sectional view.

controlled to an accuracy of ~1 nm. The standard process for removing the naturally-formed Si oxide film on the Si substrate was intentionally omitted, which led to an observation of the signal arising from the surface phonon-polariton (SPhP) of SiO_2. Next, Au (40 nm)/Ti (10 nm) were deposited on the substrate. Antenna patterns were made by electron-beam lithography, followed by a lift-off technique that cut out dumbbell-shaped openings from the metal sheet. The dumbbell shape doubled the intensity of the electric field in the narrow opening region at the central portion compared with that of a slot antenna having the same length, L. One antenna array consisted of 15x8 elements, each having the same size and dimensions. We measured the reflection spectra with a micro FTIR, which is in the infrared microscope beam line (BL-15) in the SR center, and obtained the normalized reflectivity, R, using the spectrum from Au.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the results for antenna arrays on the Al_2O_3/Si substrates. The dependence of (1-R) on the wavenumber is plotted as a function of the thickness of Al_2O_3 instead of the absorption. The thicknesses of Al_2O_3 were 0, 2, 4, 6 and 50 nm. According to a series of experiments investigating the resonant wavelength dependence on the opening length of the antenna, the resonant wavelength was about 850 cm^{-1} for devices used in the experiments. The raised portion of around 1250 cm^{-1} appearing in the result without Al_2O_3 was due to the SPhP of a SiO_2 layer naturally formed on the Si substrate. The spectral region between 1075 cm^{-1} and 1250 cm^{-1} corresponded to the stopband (reststrahl region) of SiO_2 [2], and radiation in this band was reflected by a bulk ionic crystal, resulting in a decrease in the (1-R) plot. This was confirmed by making optical antennas on a CVD-SiO_2 (50 nm)/Si substrate (Fig. 3). The spectrum was evidently different from that of the Si substrate (i.e. no Al_2O_3 on Si), and indicated that in the case of the Si substrate, the electric field penetrated into the Si substrate through the natural oxidation film, creating a spectrum consisting of the Si absorption and the SPhP. The electric field intensity in the natural oxide layer became weak with an increase in the thickness of Al_2O_3. The fraction of Al_2O_3 absorption was large with an increase in the thickness of Al_2O_3, thereby increasing the (1-R), the values of which at 1350 cm^{-1} and 1550 cm^{-1} are plotted in Fig. 4. The change was rapid until the thickness reached 6 nm, after which it became saturated with an increase in the thickness.

The spectra below ~1100 cm^{-1} differed considerably as compared with those in high wavenumbers. The reflectivity of Al_2O_3/Si in a square opening without the antenna arrays decreased monotonously as the wavenumber was increased from 750 to 1750 cm^{-1}, and there weren't any noticeable differences among different Al_2O_3 thicknesses. Thus, the reflectivity increase for the region less than 1100 cm^{-1} and the resultant reduction of (1-R) was obviously due to the effect of field enhancement by the antenna, and probably ascribed to the appearance of the stopband of Al_2O_3. In the ALD, the atomic layer is accumulated step-by-step, and it isn't unusual that the absorption peak wavelength of Al_2O_3 was different from that of amorphous Al_2O_3, ~950 cm^{-1} [4].

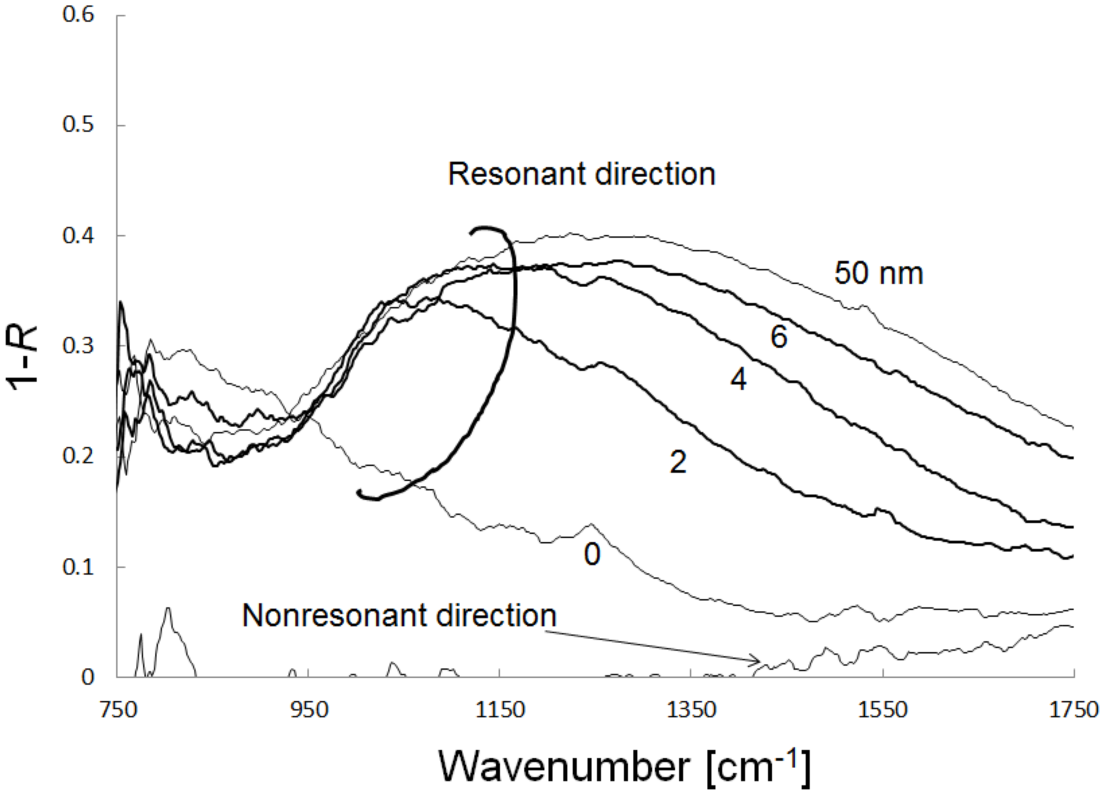


Fig. 2 1-R vs wavenumber. L= 2.5 μm, W = 0.6 μm, A = 0.2 μm, and G = 0.1μm. Each array consisted of 15 x 8 dumbbell-shaped elements. The thicknesses of Al_2O_3 were 0, 2, 4, 6 and 50 nm.

IV. CONCLUSION

The vertical distribution of the electric field produced by optical antennas could be experimentally confirmed using the ALD technique. Combining the s-SNOM with the ALD, one could obtain more accurate spatial electric field information.

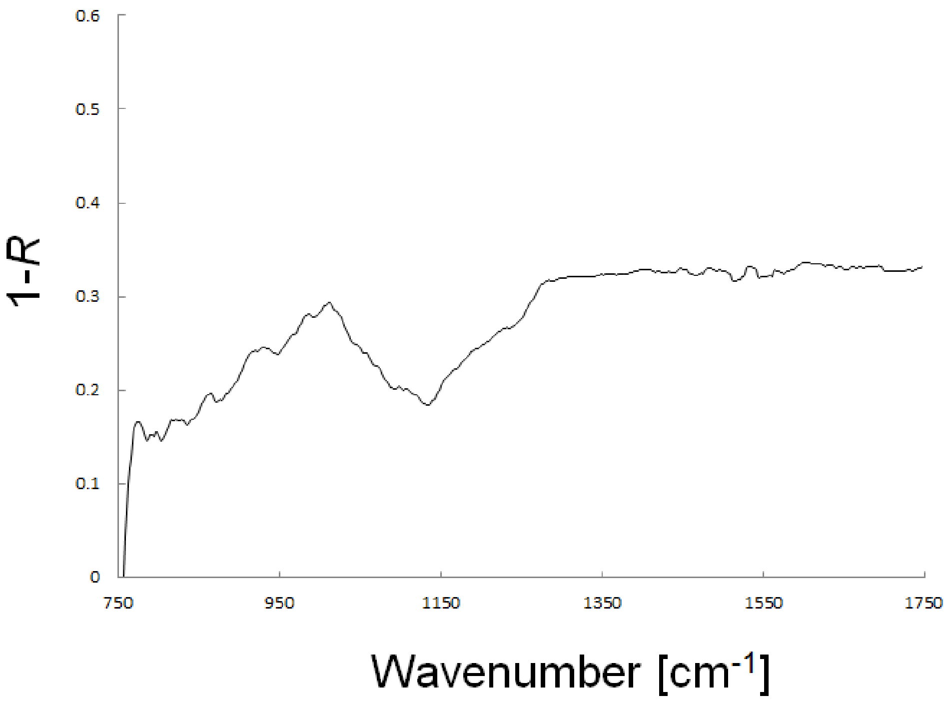


Fig. 3 1-*R* vs wavenumber for the antenna array on a 50 nm-SiO_2/Si substrate.

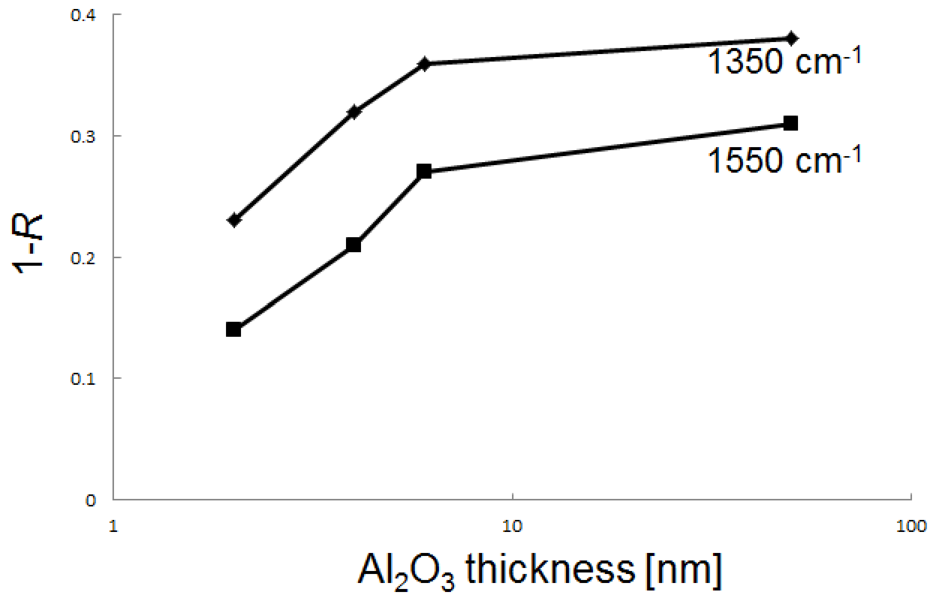


Fig. 4 1-*R* vs Al_2O_3 thickness

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