Enhancement of the electric field normal to the surface of mid-infrared slot antennas

Kouichi Tsushima[1], Syun Mori[1], Yuuki Nishimura[1], Kazuki Hishii[1], Kenichi Kasahara[1], Toyonari Yaji[2], Hideki Miyazaki[3], Naoki Ikeda[3], Hirotaka Oosato[3], and Yoshimasa Sugimoto[3]

1) College of Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan

2) SR Center, Research Organization of Science and Technology, Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu 525-8577, Japan

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

Abstract

After growing a thin Al_2O_3 layer by atomic layer deposition on a Si substrate, slot antenna arrays were formed on it. Reflectivity spectra measured in the mid-infrared range showed characteristic aspects, presumably caused by the surface phonon polariton of a SiO_2 layer naturally formed on the Si substrate. When the Al_2O_3 layer thickness was 6 nm, such spectral features disappeared. In this way, we could estimate experimentally the electric field distribution normal to the surface of the substrate.

1. Introduction

Optical antennas can enhance local field intensity. The field intensity becomes large near the antenna, which, however, falls drastically at positions distant from it, indicating an occurrence of intense localization of electric fields near the antenna, and hence, the generation of an optical hotspot. The distribution of the electric field around an optical antenna can be calculated by FDTD, and it is possible to know the field enhancement effect of the antenna by observing the reflection spectra with the use of a Fourier transform infrared (FT-IR) spectrometer [1]. If one could use, for example, scattering near-field microscopy (s-SNOM) [2], local information on the field enhancement on a plane would be available. However, such information obtained in a certain position includes data in both horizontal and vertical directions. Very little experimental work showing the field enhancement distribution of the antenna in a vertical direction is currently available in published literature. Towards that end, a thin dielectric layer was deposited on a Si substrate with the use of atomic layer deposition (ALD), and dumbbell-shaped slot antennas were fabricated on it. It was possible to grow the layer with the thickness being controlled to an accuracy of ~1 nm. By observing the spectra reflected off antenna arrays with different layer thicknesses, an understanding of the vertical field distribution could be gained (i.e. the field localization and the magnitude of the field enhancement).

2. Fabrication of slot antennas

The shape of a conventional slot antenna is rectangular. In this study, it was modified like a dumbbell so as to increase field-intensity near the feed gap at the center, and to form a single hot spot [3]. Another merit of these antennas is that the fabrication is easier than that of dipole antennas, because dipole antennas leave small metal stripes on a substrate. The antenna arrays were fabricated as follows: a thin Al_2O_3 was grown using the ALD on a Si substrate. A set of cleaning processes including HF treatment is ordinarily performed to remove an oxide film naturally formed on a Si substrate prior to deposition of dielectric layers. In this study, that process was omitted. Next, Au (40 nm)/Ti (10 nm) were deposited on the substrate. Antenna patterns were made by electron-beam lithography and a lift-off technique followed it, cutting out dumbbell-shaped openings from the metal sheet. One antenna array consisted of 15x5 elements with each having the same size and dimensions. Besides the antenna arrays, the metal sheet had 30 μm x 30 μm square openings to examine the antenna effect.

3. Results and discussions

The reflection spectrum of one antenna array was measured using a microscopic FT-IR, which is in the IR microscope beamline (BL-15) in the SR center. A globar lamp in the FT-IR was used as IR light source and an aperture size was 24 μm x 24 μm. The reflection spectrum was normalized by the reflectivity from the Au film on the substrate. Figure 1 (a) shows the plain view and cross-section view of an antenna element, and Fig. 1 (b) shows the normalized spectra of three arrays. The lengths of the elements in three arrays were 1, 1.5 and 2 μm. The polarization of incident light was perpendicular to the length direction, which was the resonant direction of antennas. The normalized reflectivity of the square opening (i.e. region without antenna elements) is also shown in Fig. 1 (b). While the reflection spectrum of the square opening decreased monotonously over the range from 750 cm^{-1} to 1750 cm^{-1}, the arrays showed distinctly different spectra. Although as L was increased, the resonance wavenumbers of the arrays became small, one can see that the reflectivity grew in the range between ~1075 cm^{-1} and ~1250 cm^{-1}.

(a)   (b)

(b)

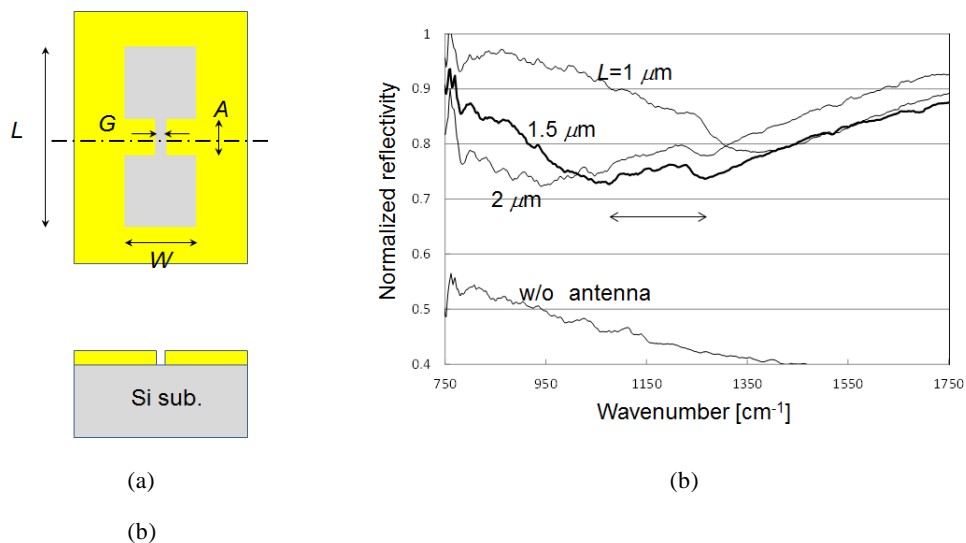**Fig. 1** Antenna arrays on a Si substrate. (a) Plain view (top) and cross-section view (bottom) of one element. W = 0.6 μm, A = 0.4 μm, and G = 0.1μm. (b) Reflection spectra by microscopic FTIR. Each array consisted of 15x5 dumbbell-shaped elements. A horizontal arrow indicates the rage from 1075 cm^{-1} to 1250 cm^{-1}.

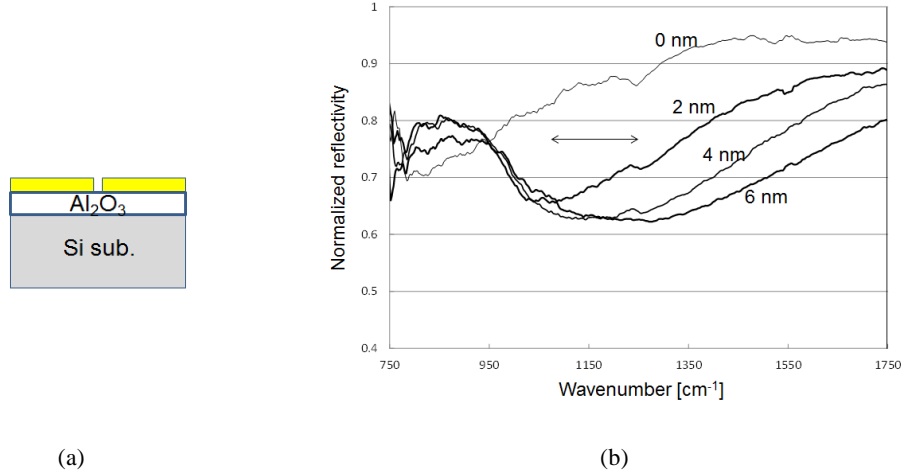Fig. 2 Antenna arrays on an Al$_2$O$_3$/Si substrate. (a) Cross-section view. L= 2.5 μm, W = 0.6 μm, A = 0.2 μm, and G = 0.1μm. (b) Reflection spectra for Al$_2$O$_3$ having thicknesses of 0, 2, 4, and 6 nm

Figure 2 (a) shows the results for antenna arrays on an Al$_2$O$_3$/Si substrate. The thicknesses of Al$_2$O$_3$ were 0, 2, 4, and 6 nm. The dip appearing around 1250 cm^{-1} weakened as the Al$_2$O$_3$ was thick, and for 6 nm, it disappeared. The measured reflectivity of the square opening region, shown in Fig. 1 (b), reflects the optical properties of Si bulk. Field enhancement occurs in the vicinity of antennas, and even taking into consideration the antenna resonance properties, the spectra of the arrays were completely dissimilar. Therefore, it is reasonably concluded that the characteristic spectral change appearing in the arrays were caused by a thin SiO$_2$ layer naturally formed on the Si substrate. Similar dip was reported to appear around 1250cm^{-1} in FTIR transmission spectra in ref. 5, where it was attributed to the surface phonon polariton (SPHP). Aside from the substrates mentioned above, antenna arrays fabricated on a CVD-SiO$_2$ (50 nm)/Si substrate were also made, which showed a broad dip around 1065 cm^{-1}. This wavenumber almost coincided with the transverse optical frequency, ω_T, of SiO$_2$. From these results, the dips that appeared around 1075 cm^{-1} and 1250 cm^{-1} are presumed to arise from the SPHP of a natural SiO$_2$ layer, corresponding to two SPHP modes which appear when the layer thickness is thin and has two interfaces [6]. In the case of phonon polariton in bulk, the frequency range between $\omega_T < \omega < \omega_L$ (longitudinal optical frequency) becomes a stop band. The reflectivity increases in that range, because photons are prohibited from being present. Two SPHP frequencies exist within the stop band. For the SPHP modes to appear, it is necessary that the straight line expressing the dispersion in the air must intersect the dispersion curves of the two-interface SPHP. A parallel wave number of the SPHP modes approaches ω/c as ω comes close to ω_T. Although incident light entered obliquely on the arrays in the FT-IR,

allowing the existence of a parallel electric component (i.e. polarization direction: perpendicular to the substrate surface), this still seems difficult to achieve, because the dispersion in the air was $\omega = cq/\sin\theta$, not satisfying the condition of $\omega < cq$ (c: light speed, q: wave number, and θ: angle measured from normal line). However, the authors believe that it isn't the case when antennas are formed. It would be necessary to take in the effect of slow light due to the antenna. The group velocity of light becomes slow underneath the antenna due to the Plasmon effect. It is possible that this affects the velocity of the parallel electric component, thereby resulting in slow velocity and excitation of the SPHP modes.

The results shown in Fig. 2 (b) are evident: the electric field intensity which a natural SiO_2 layer felt was weak with an increase in the thickness of Al_2O_3.   Reflectivity in the high wave number range dropped as the Al_2O_3 layer was thick, but it didn't vary in a striking manner below ~1050 cm^{-1}. This was because this range corresponded to the stop band of Al_2O_3 [7].   The field intensity in parallel planes below and at the air/substrate interface was calculated using the FDTD method. When the Al_2O_3 layer thickness becomes 10 nm, it drops off to about 10% of the intensity at the surface, which was in reasonable agreement with the experimental results.

4. **Conclusions**

The vertical distribution of the electric field enhancement produced by optical antennas could be experimentally confirmed. The combination of the antenna and a quantum cascade laser would yield attractive mid-infrared microscopic analysis to detect a solid state surface.

References

[1]   K.B. Crozier, A. Sundaramurthy, G.S. Kino, and C.F. Quate, *J. Appl. Phys.*, **2003**, 94, 4632.

[2] M. Brehm, T. Taubner, R. Hillenbrand, and F. Keilmann, *Nano Lett.,* **2006**, 6, 1307.

[3] V.D. Kumar and K. Asakawa,, *Photon. Nanostruct.,* **2009**, 7, 161.

[4] K. Ishikawa, H. Ogawa, and S. Fujimura, *J. Appl. Phys.*, **1999**, 85, 4076.

[5] F. Neubrech, D. Weber, D. Enders, T. Nagao, and A. Pucci, *J. Phys. Chem.C*, **2011**, 7299.

[6] M.G. Cottam and D.R. Tilley, *Introduction to surface and supperlattice excitations* 2nd ed., Bristol and Philadelphia: Institute of Physics Publishing, **2005**.

[7] D. Palik, *Handbook of optical constants of solids Ⅲ*, San Diego: Academic Press, **1998**.