Probing enhancement of an electric field perpendicular to an optical antenna surface using SiC surface phonon polaritons

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Abstract

An electric field in the normal direction enhanced by a mid-infrared circular slot antenna was estimated by observing the intensity of surface phonon polariton signals arising from the SiC surface. To know the distribution of the enhancement, a thin Al_2O_3 layer was deposited on the SiC substrate as a spacer using the atomic layer deposition. Monitoring the surface phonon polariton intensity with varying Al_2O_3 layer thicknesses allowed measurement of increasing perpendicular fields.

1. Introduction

A technique has been developed for investigating electric-field distributions of optical antennas in the depth direction by means of atomic layer deposition (ALD) [1]. One of the aims of this research is to produce rapid response and high sensitivity mid-infrared detectors by combining the field enhancement effect of an optical antenna and intersubband transitions in quantum wells. To explore additional applications of mid-infrared quantum cascade lasers, used for environmental gas sensing, it is necessary to develop high-performance mid-infrared detectors. Thus, it is essential to precisely know the actual distribution of electric field components vertical to substrate surfaces in the depth direction. This is because intersubband transitions which occur as electromagnetic waves with an electric field component perpendicular to the quantum well layer have been irradiated. Electric fields in the depth direction are calculated using the finite-difference time-domain (FDTD) method, which is a powerful means of the design of nano-optical devices. However, it is still necessary to actually evaluate the appropriateness for the obtained results, because FDTD simulations need the dispersion characteristics of media in an analytical domain and very fine discretization in space in order to correctly predict the distribution of electromagnetic waves, particularly, in the case of optical nanoantennas including metals.

The purpose of this study is to investigate the possibility of experimentally measuring the enhancement of electric fields in the normal direction and of probing their depth dependence. 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 estimate the electric field perpendicular to a substrate by varying the Al_2O_3 thicknesses. ALD is a process used to realize highly uniform thin layers by alternating exposures of a surface to vapors from two chemical reactants in a viscous-flow reactor, which grow continuously in a layer-by-layer fashion. SPhPs are bound to the interface between Al_2O_3 and SiC, and possess s-polarization. Thus, it is possible to grasp the in-depth distribution of electric fields increased by optical antennas by changing the thickness of the Al_2O_3 spacer layer. The knowledge obtained in this study is available for designing high-performance mid-infrared detectors with high-sensitivity and quick response times.

2. Fabrication of circular slot antennas

Figure 1(a) and (b) show the cross-sectional and plain views of circular slot antennas fabricated on ALD-made Al_2O_3/SiC. ALD was performed using trimethylaluminum (TMA) and H_2O along with commercially-available equipment. The thicknesses of the Al_2O_3 layers were varied from 0 to 100 nm. Next, circular slot antenna patterns were made by 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 distance of the adjacent antennas was 9 μm. The reflection spectra were measured with a micro FTIR without a polarizer, and the normalized reflectivity was obtained using the spectrum from Au.

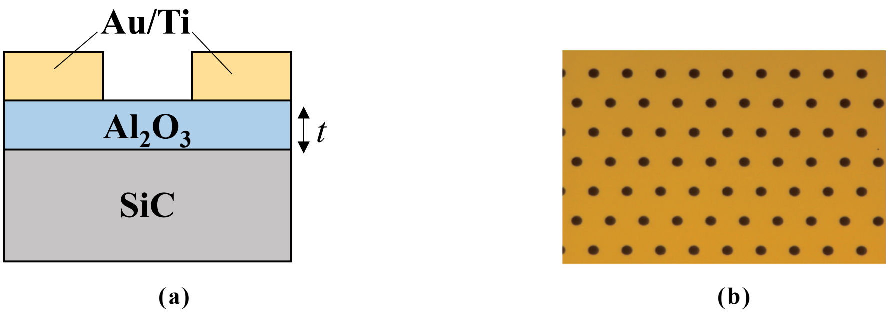


Fig. 1 (a) Cross-sectional view of a circular slot antenna fabricated on Al_2O_3/SiC and (b) Plain view of antenna array.

3. Results and discussions

Figure 2 shows the results for the normalized reflectivity of antenna arrays with the thickness, t, of Al_2O_3 being changed. The diameter of the antenna was 6 μm. When t = 0 nm, it was found that a decrease in reflectivity at 929 cm^{-1}, caused by SPhP, appeared among the Restrahlen band of SiC ranging from 800 to 970 nm. This dip almost disappeared when t = 100 nm, because the interface of Al_2O_3 and SiC was distant from the antenna, and field enhancement was weak. However, looking closer, one notices that the decrease in reflectivity due to SPhP signals was not monotonously reduced with the Al_2O_3 thickness, which is shown in Fig. 3(a). There, the dip depth was measured with reference to that of t = 0 nm. It was 85% at

t = 5 nm, and increased to 90% at t = 10 nm. The dip was smaller as t was increased over 10 nm.

Generally, as t increases, the intensity of electric fields perpendicular to the substrate surface, E_z, should be at maximum. This is easily anticipated from the following: although E_z is zero on the surface of the substrate, it starts to appear distant from the surface. E_z eventually vanishes at a great distance, thereby leading to the existence of a peak at a certain position distant from the surface. In this case, further account must be taken into the absorption in Al_2O_3. The relationship between absorption coefficient α and extinction coefficient κ is represented by $\alpha = 4\pi\kappa / \lambda$. κ of ALD-Al_2O_3 was measured by an ellipsometer and was 0.574 at 932 cm^{-1}, which was different from the data in Ref. [3]. When this value was used, α

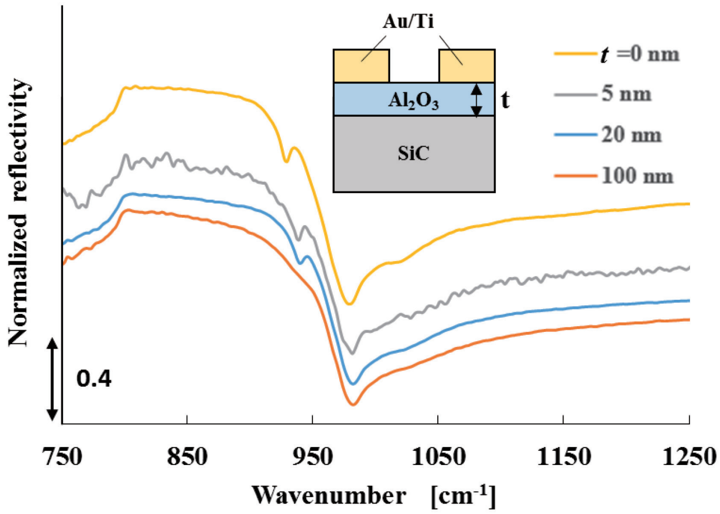
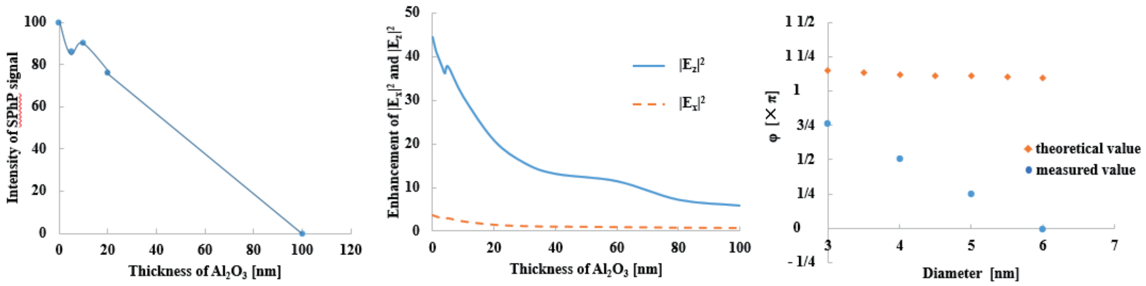


Fig. 2 Normalized reflectivity of circular-slot antenna array on Al_2O_3/SiC substrate when the thickness of Al_2O_3 was changed.

became 6.78×10^{-4} nm^{-1}. On the assumption that the Beer-Lambert law and no enhancement of electric field by the antenna, $|E_z|^2$ attenuated to 0.997 when t was 5 nm, meaning that there was only a 0.3% decrease. However, the results are different in the cases where an antenna is present. Namely, equivalent thickness of Al_2O_3 should grow due to enhanced electric field, increasing considerable attenuation of input light as it propagates into Al_2O_3. Figure 3(b) shows the results of FDTD calculation of enhancement of $|E_x|^2$ and $|E_z|^2$ vs. Al_2O_3 thickness, which was made near the edge of Au. Enhancement of $|E_z|^2$ was 45, when t = 0 nm, which was reasonably in agreement with the result shown in Fig. 3(a).

Next, the phase was calculated of the structure for air/SiC (i. e. t = 0 nm) based on the equation, $k_{SPhP}D + \varphi = 2\rho_{m,n}$. Here, k_{SPhP} is the SPhP wavenumber parallel to the substrate surface, φ is the phase change upon the circular edge, and $\rho_{m,n}$ is the mth zero point of the nth Bessel function. Moreover, k_{SPhP} was obtained calculating the dispersion characteristics for the air/SiC and using measured wavenumber of



(a) (b) (c)

Fig. 3 (a) SPhP signal intensity vs. the thickness of Al_2O_3 layer, (b) Enhancement of $|E_x|^2$ and $|E_z|^2$ with FDTD simulation, and (c) Phase dependence on diameter.

SPhP (= 932 cm^{-1}). Phase dependence on diameter is shown in Fig. 3(c), indicated as a measured value where m = 1 and n = 0 were assumed. Calculation of φ from the imaginary part of the complex reflection coefficient r_m [4] was also conducted, indicating it as the theoretical value in Fig. 3(c). There is a difference coming out of two calculation approaches, and there is a room for examination.

4. Conclusion

Distribution of electric fields perpendicular to the antennas increased by circular slot antennas was invesigated by monitoring SPhP signals. When the thickness of the Al_2O_3 layer was 100 nm, the SPhP sinal almost disappeared. The result that the electric fields enhanced by antennas hardly existed at a depth of 100 nm.

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