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Observation of the enhancement of electric fields normal to the surface using mid-infrared slot antennas and an atomic layer deposition technique

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A B S T R A C T

Optical electric field enhancement in the normal direction was experimentally investigated using mid-infrared slot antennas that were formed on a thin Al_2O_3 layer/Si substrate. The Al_2O_3 layer thicknesses could be controlled to an accuracy of a given atomic layer through the use of atomic layer deposition, and varied from 0 nm to 60 nm. An in-depth probe of the electric field was performed by observing the change in the reflection signal arising from the Restrahlen band of the natural oxide of Si formed on the surface of a Si substrate. In contrast to dipole nanoantennas, we could clearly observe Restrahlen bands of Al_2O_3 as well as the native Si oxide film. This was because the direction of the enhanced electric field was primarily parallel to the substrate surface in the slot antennas, which was different from the dipole nanoantenna having strong normal electric fields at the antenna ends. The atomic layer deposition technique provides versatile information on the electric field distribution within the depth direction, being considered complementary to the electromagnetic simulation of nanoantennas.

1. Introduction

Significant progress in mid-infrared distributed-feedback quantum cascade lasers (QCLs) capable of continuous-wave operation above room temperature has allowed for the monitoring of trace gases relating to environmental and energy issues [1,2]. To broaden the application of QCLs, photo-detectors exhibiting both high-sensitivity and high-speed are needed in the mid-infrared range. Optical antennas generate optical hotspots, and enhance local field intensity near the antenna, thereby allowing for efficient photon harvesting [3]. Thus, sufficient absorption is obtainable even from a thin absorption layer, and it is possible that a combination of optical antennas and a thin photo-absorption layer [4–6] leads to the achievement of high-performance mid-infrared detectors with high-sensitivity and quick response times. Field intensity becomes large near an antenna, and decreases rapidly with increasing distance from it. Accordingly, it is necessary to know the increased field distribution of the antenna in the vertical direction for designing mid-infrared photo-detectors equipped with antennas. The finite-difference time-domain (FDTD) method is a powerful tool for use in the design of nano-optical devices, which can calculate electric fields in the depth direction. However, it is still necessary to evaluate the appropriateness of the obtained results in a practical manner, because FDTD simulation necessitates the frequency dispersive nature of media in an analytical domain and very fine discretization in space in order to correctly predict the electromagnetic distribution, particularly, in the case of optical nanoantennas including metals. The field enhancement of the antenna can be measured by observing a reflection or transmission spectra through a micro-Fourier transform infrared (FT-IR) spectrometer [7–13]. Local information on the field enhancement is also available if one uses a scattering near-field microscopy (s-SNOM) [14]. However, such measurements alone are insufficient to ascertain the distribution of field enhancement normal to an antenna plane. To this end, a thin Al_2O_3 layer was deposited on a Si substrate through atomic layer deposition (ALD), and dumbbell-shaped slot antennas (DSAs) were fabricated on this. It was possible to grow a layer with thickness being controlled to an accuracy of ~1 nm. By observing the spectral magnitude dependence of the SiO_2 layer, which was naturally formed on the Si layer, on the Al_2O_3 thickness, we could actually gain an understanding of the vertical field localization. Unlike the surface-phonon polariton (SPhP) signals obtained in experiments using dipole nanoantennas, reflectivity increases originating from the Restrahlen

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band (or forbidden polariton band) of natural Si oxide film emerged, and we could measure their depth dependence. There have been no experiments reporting the distribution of electric field enhancement in the perpendicular direction. Reflectivity increases in the Restrahlen band due to the antenna effect were distinctly observed from ALD-made Al_2O_3 layers as well as from a SiO_2 layer. This was because the direction of the enhanced electric field was mainly parallel to the substrate surface in DSAs.

2. Fabrication of dumbbell-shaped slot antennas

The performances of optical antennas have been, so far, reported mainly using dipole structures. In this study, we used a DSA, which consisted of a rectangular opening with a small feed-gap in its center, which was cutout from a thin metal sheet [Fig. 1(a)–(c)]. *L* and *W* represent the length and width of the rectangular opening, respectively, in the figure. The length and width of the feed-gap are denoted by *A* and *G*, respectively. The feed-gap formed a nanocapacitor, leading to an intense localization of the electric field. In the radio-frequency range, the radiation pattern of a rectangular-shaped slot antenna is the same as that of a dipole antenna, with the sole difference being the reversed direction of the electric and magnetic fields. The optical dipole antenna has two hotspots at both ends. On the other hand, the DSA used in our study could easily form a single hotspot in the center [15], meaning that the DSA could convert an incident electromagnetic wave into a more localized volume, yielding increased absorption in a thinner layer. Another merit of the slot antenna is that its fabrication is easier than that of dipole antennas, because dipole antennas leave small metal stripes on substrates.

The slot antenna arrays were fabricated as follows: a thin Al_2O_3 was grown using ALD on a Si substrate. A set of cleaning processes including HF treatment is ordinarily performed to remove the Si oxide film naturally formed on a Si substrate prior to dielectric layer deposition, but this process was omitted to use the native oxide layer as a marker for investigating electric field distribution in the depth direction. ALD is a process for the deposition of highly uniform thin layers by alternating exposure of a surface to vapors from two chemical reactants in a viscous-flow reactor. Al_2O_3–ALD was performed using trimethylaluminum (TMA) and H_2O along with commercially-available equipment. The non-uniformity of the nominal thickness was 0.3% in a 3-in. wafer. TEM images showed that Al_2O_3 ALD films grown at 200 °C were smooth [Fig. 1(d)]. Next, Au (40 nm)/Ti (10 nm) were deposited on the substrate. The thickness of Au was determined to be thicker than the skin depth of Au (26 nm). The plasmonic mode excited on the top surface of Au was not influenced by the bottom surface under these conditions, and the resonant frequency was not influenced by the thickness of the Au. Antenna patterns were made by electron-beam lithography and a lift-off technique followed, cutting out dumbbell-shaped openings from a metal sheet. The slot antenna in the radio-frequency domain resonates when the long side of a rectangle is half of the wavelength λ of the incident radiation. The scaling, however, fails in the mid-infrared range, since the metals act as a strongly-coupled plasma, and the length of the long side shortens. One antenna array consisted of 15×5 elements, each having the same size. Besides the antenna arrays,

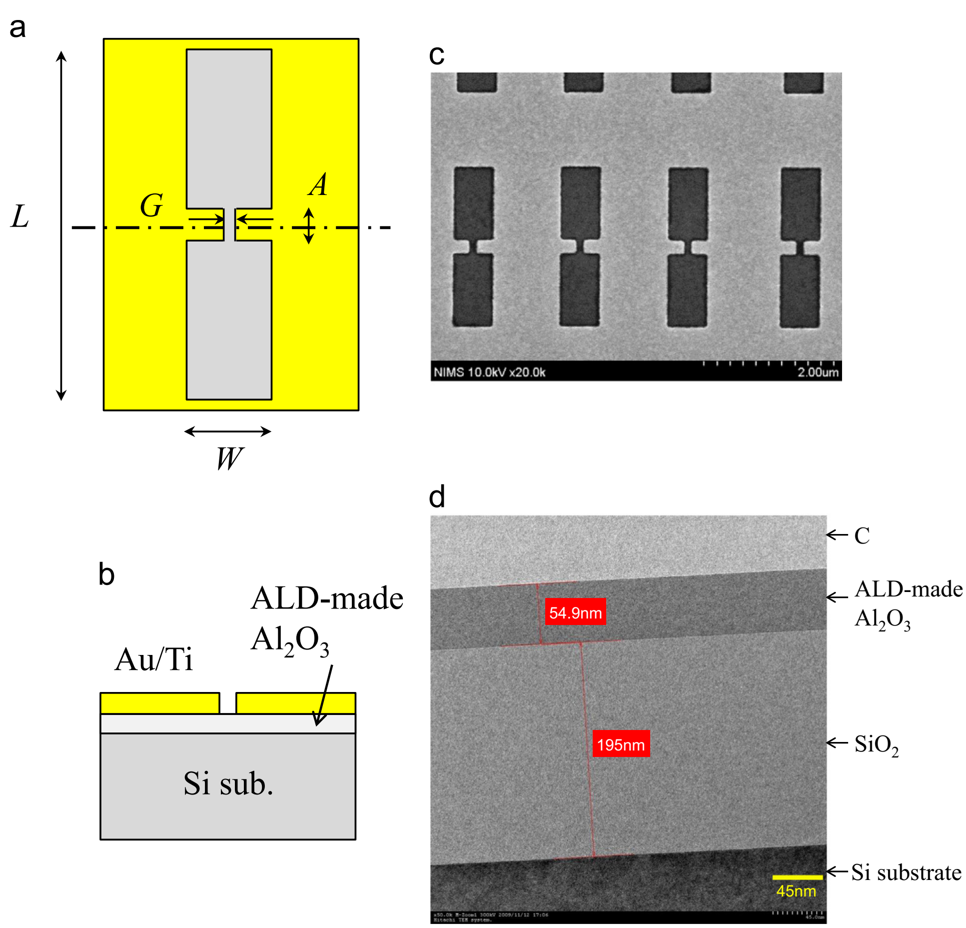

Fig. 1. Dumbbell-shaped antenna structure. (a) Plane view and (b) cross-sectional view. *L*: length, and *W*: width of the rectangular opening. *A*: length, and *G*: width of the feed-gap. (c) Surface image of the fabricated DSAs. (d) Cross-sectional view of a structure fabricated to measure the thickness of ALD-made Al_2O_3 using TEM. In this case, Al_2O_3 thickness is 54.9 nm.