Resonant terahertz transmission in subwavelength metallic hole arrays of sub-skin-depth thickness

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We study surface-plasmon-enhanced terahertz transmission through subwavelength metallic hole arrays of sub-skin-depth thickness. Dynamic evolution of surface-plasmon resonance in terms of array thickness is characterized by use of terahertz time-domain spectroscopy in the frequency range 0.1–4.5 THz. A critical thickness of lead array film is observed, above which surface-plasmon coupling of terahertz pulses begins and is enhanced rapidly as the array thickness is increased toward the skin depth. The experimental results indicate that high-efficiency extraordinary terahertz transmission can be achieved at an array thickness of only one third of skin depth. © 2005 Optical Society of America

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The extraordinary transmission of electromagnetic waves through metallic films of periodic subwavelength hole arrays has stimulated significant interest in recent years. Optical transmission efficiency higher than unity has been demonstrated when it is normalized to the area occupied by the holes.[1] Because of the resonant excitation of surface-plasmon polaritons (SPPs) at the metal–dielectric interface, extraordinary optical transmission can be observed at much lower frequencies than that of the cutoff defined by the dimensions of the subwavelength holes.[2,3] Extensive experimental and theoretical studies have been carried out not only to understand the fundamental physics behind this extraordinary transmission but also to explore the potential applications in the integrated photonic devices and nanofabrication processing.[4–7] Sub-diffraction-limited nanolithography has been demonstrated by use of surface-plasmon-enhanced transmission of UV light through a subwavelength hole array.[7]

Recently, extraordinary transmission of terahertz pulses was observed in both metallic[8–12] and semiconductor[13–15] arrays. The characteristics of surface-plasmon-enhanced terahertz transmission have been studied in terms of various parameters of the subwavelength hole arrays, such as the lattice constant, the dielectric constant of the constituent metals, the shape of the holes, and the thickness of the semiconductor arrays. Enhanced terahertz transmission was experimentally demonstrated in subwavelength arrays made from both good and poor electrical conductors.[9] The amplitude transmission was found to rise with higher values of the ratio of the real to the imaginary dielectric constant of the constituent metals, $-\varepsilon_{\mathrm{rm}}/\varepsilon_{\mathrm{im}}$, for which the dielectric function follows the Drude model. The influence of hole shape on the terahertz transmission was dramatically different from that of the optical region.[8,10] In the arrays of doped silicon an exponential decay in the peak transmission was observed as the array thickness increased to orders of magnitude higher than the skin depth.[15] In addition, a redshift and a reduction in transmission amplitude were demonstrated when the surrounding dielectric constants were increased.[13]

So far, investigations of SPP resonances have focused on optically thick subwavelength hole arrays in both optical and low-frequency regions. It is intriguing how the SPP resonances are developed in metallic arrays of sub-skin-depth thickness. In this Letter we demonstrate resonant terahertz transmission through subwavelength hole arrays patterned on metallic films with thickness less than skin depth. Experimental results have revealed a critical array thickness above which the SPP resonance occurs. The maximum amplitude transmission is achieved when the thickness of metal films approaches skin depth. However, enhanced terahertz transmission of up to nine tenths of the maximum transmission can be realized at a film thickness comparable to the skin depth at wavelengths of light that is only one third of the skin depth at 0.55 THz. This finding may extensively reduce the metal thickness in the applications of terahertz SPPs in biosensing,[16] high-throughput terahertz near-field imaging systems,[17] and plasmonic terahertz optoelectronic devices.[13]

The metallic arrays studied here were made from lead on a 0.64-mm-thick p-type silicon wafer with a resistivity of $\rho = 20\ \Omega$ cm. A conventional photolithographic process was used to form the $100\ \mu\mathrm{m} \times 80\ \mu\mathrm{m}$ rectangular holes with a lattice constant of $160\ \mu\mathrm{m}$. Terahertz time-domain spectroscopy transmission measurements were performed to characterize the SPP resonance of the subwavelength arrays. The detailed experimental setup was described previously.[8,9,13] The amplitude transmission of the arrays is depicted by the ratio between the sample and the reference spectra.

The value of the skin depth of electromagnetic waves in metal is determined by the penetration distance at which the electric field falls to $1/e$. The SPPs, which propagate on the metal–dielectric interface, decay exponentially in both media. The complex wave vector inside the metal perpendicular to the in-

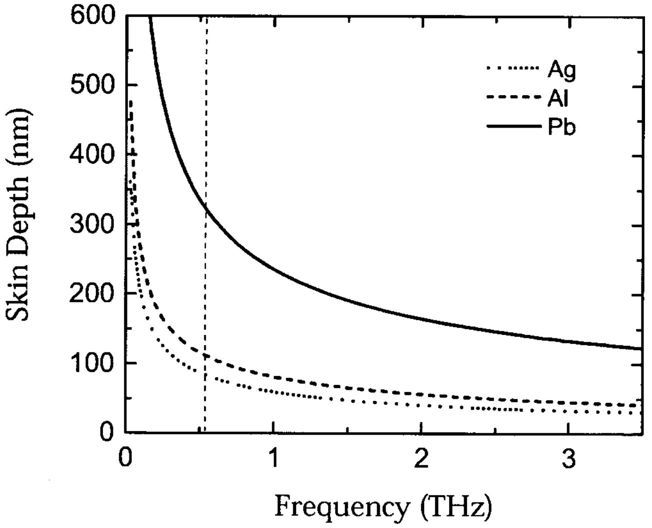

Fig. 1. Frequency-dependent skin depths of Pb, Al, and Ag calculated from the published values of the dielectric constants. Vertical dotted line, the [±1,0] surface-plasmon mode at 0.55 THz for the Pb–Si interface.

terface is given as[18,19]

$$k_z = \left(\frac{\omega}{c}\right)\left(\frac{{\varepsilon_m}^2}{\varepsilon_m + \varepsilon_d}\right)^{1/2}, \qquad (1)$$

where c is the speed of light in vacuum; ω is the angular frequency; $\varepsilon_m = \varepsilon_{mr} + i\varepsilon_{mi}$ is the complex dielectric constant of metal, ϵ_d is the dielectric constant of the medium, in our case $\varepsilon_d = 11.68$ for silicon; the lightly doped silicon does not make a contribution to the imaginary dielectric constant. At terahertz frequencies, the dielectric constant of metals is several orders of magnitude higher than that of the surrounding dielectric medium, $\varepsilon_m \gg \varepsilon_d$. So, Eq. (1) can be approximated by the simple relationship

$$k_z = (\omega/c)\sqrt{\varepsilon_m}. \qquad (2)$$

Since only the imaginary part of k_z causes exponential decay of the electric fields, the skin depth is defined as

$$\delta = \frac{1}{\mathrm{Im}(k_z)} = \frac{c}{\omega}\frac{1}{\mathrm{Im}(\sqrt{\varepsilon_m})}. \qquad (3)$$

Based on this relation, we calculate the skin depths of lead (Pb), aluminum (Al), and silver (Ag) from the published values of the dielectric constants of metals.[20] The frequency dependence of the skin depth in the frequency range of our interest is plotted in Fig. 1. At 0.55 THz, the primary surface plasmon [±1,0] resonance, the skin depths for Pb, Al, and Ag are 320, 110, and 83 nm, respectively.

We chose Pb as the constituent metal of the arrays for two reasons. First, extraordinary terahertz transmission in Pb subwavelength hole arrays has been demonstrated with an amplitude efficiency of up to 82% at 0.55 THz, which is very close to the performance of arrays made from good electrical conductors such as Ag, Al, and Au. Second, the skin depth of Pb at 0.55 THz is 320 nm, nearly three times that of Ag and Al. It thus provides a large dynamic range to characterize the evolution of SPP resonance at sub-skin-depth thickness. Pb arrays with various thicknesses ranging from 60 to 1000 nm were prepared. In the terahertz time-domain spectroscopy (THz-TDS) measurements, the input terahertz pulses are polarized along the minor axes (80 μm) of the rectangular holes and penetrate the array at normal incidence. In Fig. 2, evolution of the SPP resonance as a function of the array film's thickness is depicted in the Fourier-transformed spectra of the reference and the samples. When the array film is thin, the spectrum shows no resonance but similar features of the reference spectrum with attenuation. At 64 nm, which is observed as a critical thickness for the Pb array, the SPP resonance excited at the Pb–Si interface appears in the spectrum. Above this critical thickness, the resonance peak is enhanced with a thicker array film.

In the experiments we found that the deterioration of metal surfaces of the arrays may cause the decline in transmission efficiency. To keep surface-dependent variation to a minimum, the THz-TDS measurements were carried out immediately after completion of the metallization. The frequency-dependent amplitude transmission of arrays with different film thicknesses is shown in Fig. 3, which clearly reveals two regions of thickness dependence. Below the critical thickness, 64 nm, the frequency-dependent transmission is nearly flat, showing no resonance peak. Above the critical thickness, a resonance at 0.55 THz appears in the spectra, whose amplitude increases with array thickness while the background transmission is reduced at the same time. This resonance is attributed to the excitation of SPPs at the Pb–Si interface. At terahertz frequencies, the resonant wavelength of a rectangular array at normal incidence is given approximately by $\lambda_{sp}^{m,n} \cong l\sqrt{\varepsilon_d}/\sqrt{m^2+n^2}$, where l is the lattice constant of the array and m and n are the mode indices of the SPPs.[8] The resonance at 0.55 THz corresponds to the [±1,0] surface-plasmon mode for arrays with $l = 160$ μm at the Pb–Si interface. Immediately above the critical thickness, the resonance amplitude is very sensitive to the thickness of arrays.

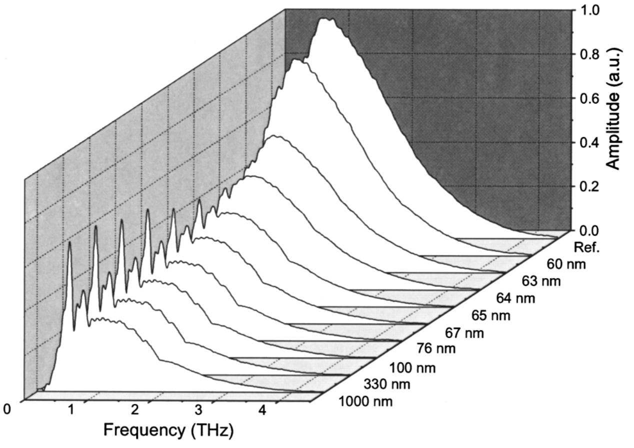

Fig. 2. Fourier-transformed spectra of the transmitted terahertz pulses through the reference and subwavelength Pb hole arrays of various film thicknesses.

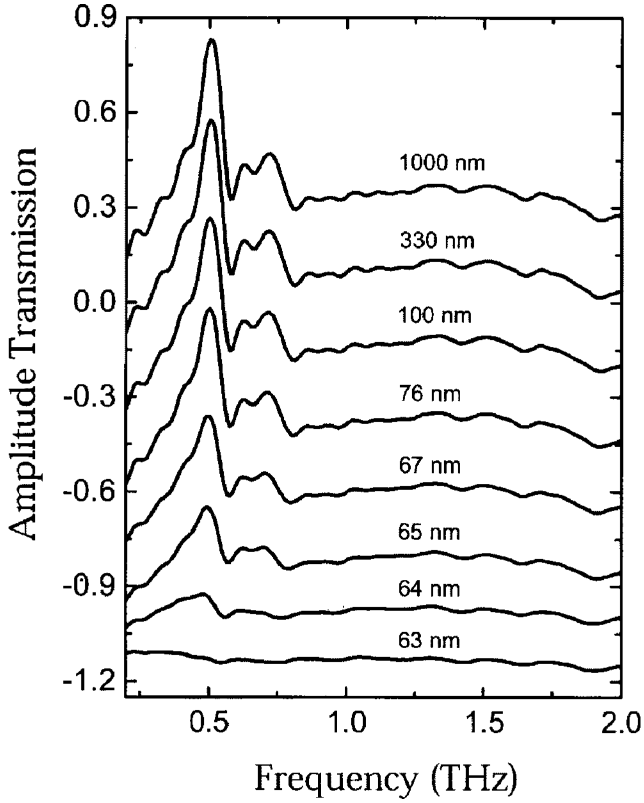

Fig. 3. Measured amplitude transmission of Pb arrays of various thicknesses. The curves are vertically displaced for clarity.

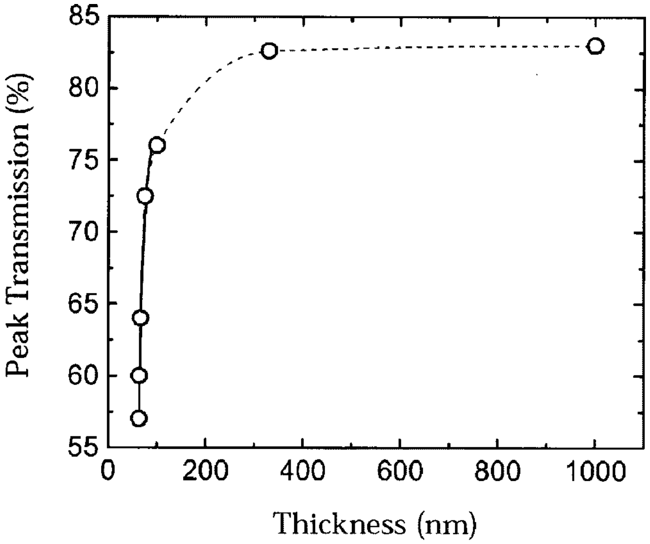

Fig. 4. Measured peak amplitude of the [±1,0] surface-plasmon mode at 0.55 THz as a function of Pb thickness (open circles, connected by a dashed curve to guide the eye). The solid curve is an exponential fit for the region of array thickness below 100 nm.

The dependence of the peak transmission on the thickness above the critical thickness is shown in Fig. 4. The amplitude transmission efficiency increases exponentially when the array thickness is below 100 nm. It then saturates gradually and approaches the maximum at the skin depth.

It is worth noting that a transmission efficiency as high as 76% is achieved at the array thickness of 100 nm, only one third of the skin depth. This value is more than nine tenths of the maximum transmission efficiency achieved at skin depth. For comparison, we have fabricated two additional arrays of the same structure, but made from Ag and Al. The film thicknesses (27 nm for Ag and 36 nm for Al) are also one third of their corresponding skin depths. The measured transmission efficiencies are 83.5% and 77.5%, respectively, for Ag and Al arrays, all above nine tenths of their maximum transmission efficiencies.

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