Effect of dielectric properties of metals on terahertz transmission in subwavelength hole arrays

Abul K. Azad, Yuguang Zhao, and Weili Zhang

School of Electrical and Computer Engineering, Oklahoma State University, Stillwater, Oklahoma 74078

Mingxia He

School of Electrical and Computer Engineering, Oklahoma State University, Stillwater, Oklahoma 74078, and College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

Received April 3, 2006; accepted May 31, 2006;
posted June 14, 2006 (Doc. ID 69592); published August 9, 2006

We study the influence of dielectric function of metals on the transmission properties of terahertz pulses through periodically patterned subwavelength holes. Because of a drastic increase in the value of dielectric constants, most metals become highly conductive at terahertz frequencies. Extraordinary terahertz transmission is observed in subwavelength hole arrays made from both good and poor electrical conductors. The measured transmittance of terahertz pulses is found to be enhanced with increasing ratio of the real to the imaginary dielectric constant of the constituent metals, for which the dielectric function follows the Drude model.

OCIS codes: 320.7120, 240.6680.

Extraordinary transmission of light in subwavelength metallic hole arrays is generally interpreted as the result of resonant excitation of surface plasmon polaritons (SPPs) at the metal–dielectric interfaces.[1–7] The role of complex dielectric function of metals $\epsilon_m=\epsilon_{rm}+i\epsilon_{im}$ is essential in the establishment of SPP-enhanced transmission of electromagnetic waves. For most metals, the real part of dielectric constant ϵ_{rm} is negative. Experimental results on the enhanced transmission of light in metallic structures revealed that the ideal metals in the optical frequency region are characterized by the large ratio of the real to the imaginary dielectric constant $-\epsilon_{rm}/\epsilon_{im}\gg 1$. The SPP-enhanced transmission efficiency of light is increased with higher ratio $-\epsilon_{rm}/\epsilon_{im}$.[2,6]

At terahertz (THz) frequencies, the dielectric constant of metals is several orders of magnitude higher than that at optical frequencies. For the nontransition metals, such as Ag and Al, the imaginary dielectric constant ϵ_{im} is much higher than the absolute value of the real dielectric constant $-\epsilon_{rm}$.[8] However, the appropriate surface corrugation gives rise to an effective dielectric constant that favors the establishment of SPPs even with the ratio $-\epsilon_{rm}/\epsilon_{im}<1$ (Refs. 9 and 10) in both the THz and microwave frequency regions.[10–19] In particular, enhanced THz transmission was also demonstrated through hole arrays patterned in highly doped semiconductors, which exhibit metallic properties in the THz region.[10,13]

In the optical spectral region, owing to the different ratio $-\epsilon_{rm}/\epsilon_{im}$, the transmission properties of light showed a large difference in the arrays made from Ag, Au, and Cr.[1,2] The transmission efficiency of the Ag arrays is several times higher than that of the Ni arrays with the same structure.[6] In this Letter we investigate the effect of dielectric properties of metals on the SPP-enhanced transmission of subwavelength hole arrays at THz frequencies. Extraordinary transmission at two pronounced surface plasmon $[\pm1,0]$ resonance modes centered at 0.55 and 1.60 THz, for metal–Si and metal–air interfaces, respectively, is investigated by THz time-domain spectroscopy (THz-TDS). We find that the resonant THz transmission rises with the higher ratio $-\epsilon_{rm}/\epsilon_{im}$ for metals with dielectric function following the Drude model. This result is consistent with the observation at optical frequencies.[2,6] However, because of the significant increase in the value of dielectric constants, the gap in the resonance peaks between arrays made from different metals is narrowed down extensively compared with that of the resonant transmission of light. In particular, extraordinary THz transmission of an array made from Pb, a generally poor electrical conductor, is observed to approach up to a $68.2\pm0.5\%$ transmittance.

Two types of metallic arrays were prepared here: array-on-silicon samples with patterned metal film on blank silicon substrate for the metal–Si $[\pm1,0]$ mode,[11] and freestanding metallic arrays for the metal–air $[\pm1,0]$ mode.[13] The array-on-silicon samples were lithographically fabricated on a 0.64 mm thick, p-type silicon wafer with a resistivity of $\rho=20\ \Omega$ cm. A pattern of 100 μm $\times$ 80 μm rectangular hole array was structured on an optically thick metal layer,[14] 120 nm for Ag and Al and 330 nm for Pb, by thermal evaporation.[11] The freestanding metallic arrays were prepared by depositing a 180 nm optically thick metal layer of Ag, Al, and Pb, respectively, on both surfaces of a 50 μm thick silicon core with an existing array of 75 μm $\times$ 45 μm elliptical through holes patterned by reactive ion etching.[13] The silicon core has an n-type resistivity of $2\times10^{-3}\ \Omega$ cm and an amplitude absorption length of less than 1 μm at 1 THz. The periodicity of all the arrays is 160 μm. A 4.5 THz broadband THz-TDS system is employed to measure the transmitted THz pulses though the arrays.[11,13]

The dielectric function of the nontransition metals such as Ag, Al, and Pb can be well described by the Drude model.[8] Based on the experimentally determined parameters given in Ref. 8, Fig. 1 shows the frequency-dependent Drude dielectric constants of such metals at THz frequencies. The absolute values of both the real and the imaginary dielectric constants are several orders of magnitude higher than that at optical frequencies.

To characterize the $[\pm1,0]$ metal–Si resonance mode, the array-on-silicon sample is oriented with the minor axis of the rectangular holes parallel to the polarization of the THz electric field.[14] In the experiments, to keep surface-dependent variation due to the deterioration of metal surface to a minimum, all the arrays made from different metals were fabricated in the same day, and the THz-TDS measurements were carried out within the next 24 h. During the time period, after the fabrication and before the measurements, the metal surface was protected with photoresist.[14] Figure 2 illustrates the amplitude transmission of the arrays made from Ag, Al, and Pb.

At normal incidence, the resonant wavelengths for the excitation of the THz SPPs of a rectangular lattice structure are given approximately by $\lambda_{sp}^{m,n} \cong L(\epsilon_d)^{1/2}/(m^2+n^2)^{1/2}$, where ϵ_d is the dielectric constant of surrounding material, L is the lattice constant, and m and n are the integer mode indices.[20] Based on this relation the calculated $[\pm1,0]$ resonance mode is located at 0.55 THz for the metal–Si interface, where $\epsilon_d=11.68$ for silicon. The measured resonance is observed at a slightly lower frequency than the calculation because of partial superposition with the Wood's anomaly as shown in Fig. 2.[11,13]

At 0.55 THz, the ratios $-\epsilon_{rm}/\epsilon_{im}$ for Ag, Al, and Pb are 0.12, 0.03, and 0.01, respectively, which indicate that Ag is still the better metal than others, and is expected to show resonance with higher transmission.[6] As shown in the inset of Fig. 2, the Ag array realizes the highest transmittance of $76.5\pm0.3\%$, while it is attenuated to $73.0\pm0.3\%$ and $68.2\pm0.5\%$, respectively, for Al and Pb arrays, indicating that the transmission increases with the higher ratio $-\epsilon_{rm}/\epsilon_{im}$. This trend is consistent with the observation in the optical frequency region.[2,6] It

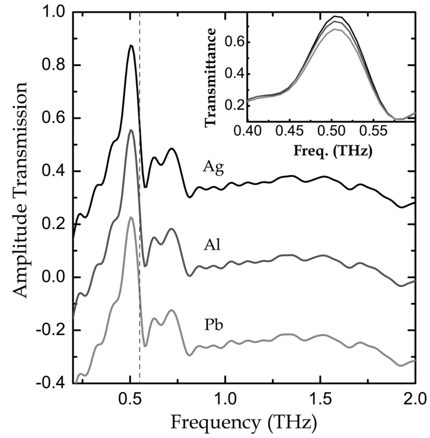

Fig. 2. (Color online) Measured amplitude transmission of the array-on-silicon samples made from Ag, Al, and Pb. For clarity, the spectra of Al and Pb arrays are moved down by 0.3 and 0.6, respectively. The vertical dashed line indicates the calculated $[\pm1,0]$ metal–Si resonance mode at 0.55 THz. Inset, corresponding transmittance.

is noted that the transmittance is not necessarily proportional to the ratio $-\epsilon_{rm}/\epsilon_{im}$ because of the complex mechanism behind this phenomenon as discussed later. The resonance linewidths for arrays made from different metals have very similar features, showing no clear evidence to depend on the imaginary dielectric constant as observed in light transmission.[2] Compared with these excellent metals, Pb is generally considered a poor electrical conductor. However, enhanced THz transmission with a peak transmittance of $68.2\pm0.5\%$ is observed through the Pb array. The dielectric constant of Pb is $\epsilon_{Pb}=-14.5+12.3i$ at $\lambda=800$ nm, and $\epsilon_{Pb}=-2.0\times10^3 +1.6\times10^5 i$ at 0.55 THz. The dramatic increase in dielectric constant enables Pb to behave as a better metal toward the SPP-enhanced THz transmission.

Transmission measurements of another $[\pm1,0]$ resonance mode at 1.60 THz, for the metal–air interface of freestanding metallic arrays, were also carried out. Before coating different metals on the silicon-array core, the previous metal films were removed completely by wet etching. In the measurements, the array is oriented with the minor axis of elliptical holes along the polarization of the THz electric field, and air is used as the transmission reference. We consider the metal-coated silicon core as a freestanding metallic array because the SPP-enhanced transmission depends only on dielectric properties of the in-plane metal surfaces of skin-depth thickness and is insensitive to the core material of the array and the hole walls.[6] As shown in Fig. 3, the peak transmittance at the 1.60 $[\pm1,0]$ THz resonance mode of Ag, Al, and Pb are $67.0\pm0.5\%$, $65.0\pm0.4\%$, and $52.2\pm0.7\%$, respectively. The ratios $-\epsilon_{rm}/\epsilon_{im}$ for Ag, Al, and Pb are 0.36, 0.08, and 0.04, respectively, at 1.60 THz. The transmission enhancement through these arrays shows similar properties as observed at the $[\pm1,0]$ metal–Si resonance, 0.55 THz.

Besides the metal arrays of skin-depth thickness, we have fabricated array-on-silicon samples with different thicknesses to verify the experimental results

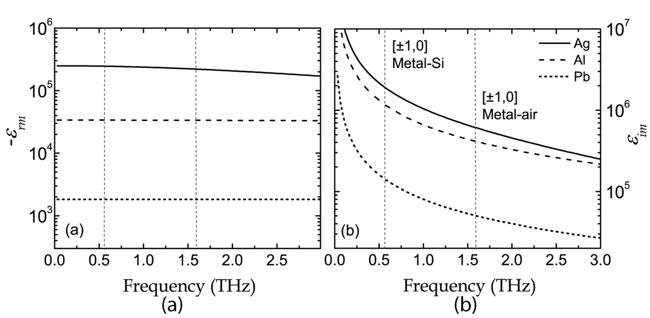

Fig. 1. Frequency-dependent Drude model dielectric constants of Ag, Al, and Pb in the THz region (Ref. 8): (a) real dielectric constant $-\epsilon_{rm}$; (b) imaginary dielectric constant ϵ_{im}. The vertical dashed lines indicate the observed $[\pm1,0]$ metal–Si resonance mode at 0.55 THz and the $[\pm1,0]$ metal–air mode at 1.60 THz.

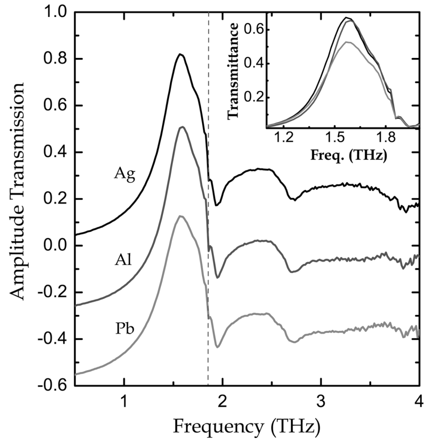

Fig. 3. (Color online) Measured amplitude transmission of the freestanding metallic arrays made from Ag, Al, and Pb. For clarity, the spectra of Al and Pb arrays are moved down by 0.3 and 0.6, respectively. The vertical dashed line indicates the calculated $[\pm 1,0]$ metal–air resonance mode. Inset, corresponding transmittance.

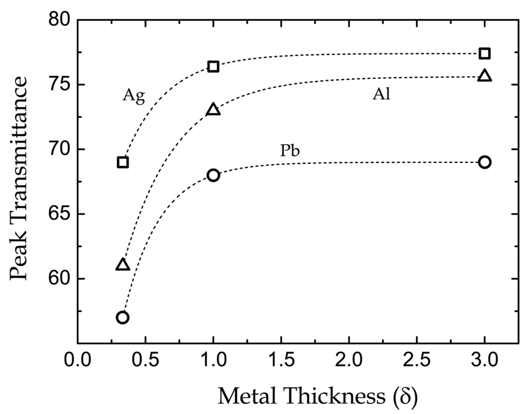

Fig. 4. Peak transmittance at the 0.55 $[\pm 1,0]$ THz metal–Si mode for arrays made from Ag, Al, and Pb with different metal thicknesses. The dashed curves are to guide the eye.

observed above. Figure 4 presents the peak transmittance measured at the 0.55 $[\pm 1,0]$ THz resonance mode for the Ag, Al, and Pb arrays. With metal thicknesses of one-third and three times of the skin depth δ, the comparison of peak transmittance for different metals remains the same trend as observed with one skin-depth thickness, demonstrating the consistency of our measurements as well as proving that the propagation of the THz wave through the metal films does not contribute substantially to the SPP-resonant transmission.

The difference in resonant transmission for arrays made from different metals has primarily arisen from the difference in effective propagation length of SPPs, determined mainly by internal damping, radiation, and scattering damping.[3] At THz frequencies, the imaginary propagation vector along the metal–dielectric interface approximately given as $k_i = k_0\epsilon_d^{3/2}/(2\epsilon_{im})$ (Ref. 11) governs the internal damping, where k_0 is the wave vector of electromagnetic wave in vacuum. The measured transmission of the metal arrays indeed decreases with increasing k_i. On a rough metal surface, besides the internal absorption, radiation and scattering damping also modify the propagation length.[3] As a result, the effective propagation lengths for different metals can be extensively reduced, leading to the difference in the resonant transmission. However, in-depth theoretical investigation is needed to further understand this phenomenon.

This study was partially supported by the National Science Foundation and the Oklahoma Experimental Program to Stimulate Competitive Research for the National Science Foundation. M. He acknowledges the financial support from the China Scholarship Council. W. Zhang's e-mail address is wwzhang@okstate.edu.

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