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Enhanced transmission of THz radiation through subwavelength holes

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We present measurements of the transmission of terahertz radiation through periodic arrays of holes made in highly doped silicon wafers. The size of the holes, 70×70 μm, is significantly smaller than the radiation wavelength $\lambda \simeq 500$ μm. Sharp resonances and enhanced transmissions are observed. This unusual transmission is attributed to the resonant tunneling of surface-plasmon polaritons that can be excited on doped semiconductors at terahertz frequencies.

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In 1998 Ebbesen *et al.* reported intriguing measurements of the optical transmission through thin-film metal gratings.[1] In this and subsequent works[2–7] it was nicely demonstrated that the optical transmission through subwavelength holes in metal films can be enhanced by several orders of magnitude. Although the explanation for this enhanced transmission is still under debate,[8–10] most of us agree that it is due to the grating assisted generation of surface-plasmon polaritons (SPP's), the tunneling of these SPP's through the holes and the subsequent coupling of the SPP's into radiation on the other side of the film.[6,11–14] This enhanced transmission may find a wide number of applications in fields such as near-field microscopy, photolithography, high-density optical data storage, and optical displays. After the recent demonstration of terahertz (THz) near-field imaging using subwavelength apertures,[15] high throughput subwavelength structures are of great interest for the development of sensitive THz imaging systems.[16] These systems will be used to probe inorganic nanostructures or individual cells.

To date all the experiments on enhanced transmission through gratings of subwavelength holes have been done at optical frequencies.[17] The transmission characteristics of dichroic filters and subwavelength gratings on gold structures have been studied by Winnewisser *et al.*[18] and by Filin *et al.*,[19] respectively. These results could be explained using solely classical diffraction theory and significant transmission was obtained only at frequencies above the cutoff frequency defined by the cavities. In this article we present the first measurements of enhanced THz transmission through gratings of subwavelength holes. As it is demonstrated below, we have structured gratings in doped Si with the appropriated doping and dimensions to excite SPP's and generate a resonant transmission at frequencies well below the cutoff.

Surface-plasmon polaritons propagate on interfaces between dielectrics and metals. Defining the permittivity of a material as the imaginary quantity $\epsilon(\omega)=\epsilon'(\omega)+i\epsilon''(\omega)$; dielectrics are materials with a positive $\epsilon'(\omega)$, while for metals $\epsilon'(\omega)$ is negative. The imaginary part of the permittivity $\epsilon''(\omega)$ is related to dissipation. In metals $\epsilon''(\omega)$ is proportional to the inverse of the collision time of the electrons or, in other words, is inversely proportional to the lifetime of the electronic collective oscillation defining the SPP's. The permittivity of most metals is such that at optical frequencies $-\epsilon'(\omega) \gg \epsilon''(\omega)$. For instance, $-\epsilon'/\epsilon''=12.96$ in gold at $\lambda=1\,\mu$m ($\omega/2\pi=300$ THz).[20] However, at lower frequencies dissipation becomes more important. In the microwave regime the permittivity of metals is essentially imaginary. For gold $-\epsilon'/\epsilon''=0.16$ at $\lambda=300$ μm ($\omega/2\pi=1$ THz); whereas $-\epsilon'/\epsilon''=0.02$ at $\lambda=3$ mm ($\omega/2\pi=100$ GHz). It has been experimentally demonstrated that a small value of the ratio between the real and the imaginary parts of the permittivity leads to a lower enhancement of the SPP's assisted transmission through gratings and to broader resonances than if this ratio is large.[3] However, significant enhancement of the transmission can be obtained even for small values of $-\epsilon'/\epsilon''$. As it was pointed out by Martín-Moreno *et al.*[21] the corrugation on the surface leads to an effective impedance or permittivity for surface modes. This effective impedance favors the establishment of SPP's and leads to the enhanced transmission. Also the skin depth or the absorption length of the electromagnetic wave might be very small in materials with low values of $-\epsilon'/\epsilon''$, which reduces the effect of the dissipation and enhances the establishment of SPP's.

Our samples are made of doped silicon. Due to the dielectric properties of doped semiconductors SPP's can be excited at terahertz frequencies. We have measured the zero-order transmission, i.e., the transmission of an incident wave normal to the sample surface, through square two-dimensional gratings of holes. The size of the holes w, 70×70 μm, remains constant for all samples; the thickness of the grating d (hole depth) and the lattice constant a_0 were varied. These structures exhibit a resonant transmission at wavelengths much larger than the hole size. The measured transmission efficiency is up to nearly two orders of magnitude larger than the expected classical diffraction transmission.

The initial material used for our experiments were commercially available Si wafers,[22] doped with phosphorus with a doping concentration of $N=10^{18}$ cm^{-3} and a thickness of 280 μm. To obtain thinner wafers they were polished with a Logitech PM5 polishing machine. Thinner wafers than 100 μm were too fragile to be further processed. The grating of holes was structured with a Disco DAD 321 wafer saw. The thickness of the sawing blade, which defines the lateral size of the holes was $w=70$ μm. Cuts with a depth of half the wafer thickness and a separation of a_0 were done on one side. After that, similar cuts but perpendicular to the previous ones were done on the other side of the wafer. This procedure provides a square grating of 70×70 μm holes with a lattice constant a_0 in the x and y directions. In the lower inset

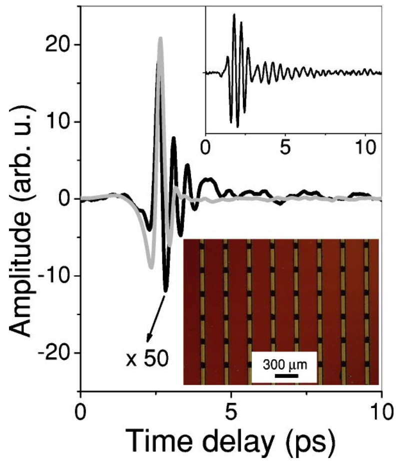

FIG. 1. (Color online) Terahertz time domain pulses. Gray line, reference measurement. Black line, zero-order transmission through a square grating of holes with dimensions $w=70\times 70$ μm, lattice constant $a_0=400$ μm and thickness $d=100$ μm. This measurement is magnified by a factor of 50. The zero-order transmission of a similar grating but with a thickness $d=280$ μm is displayed in the upper inset. The lower inset shows a photograph made with an optical microscope of a grating with $a_0=300$ μm. The dark squares on this photograph are the holes.

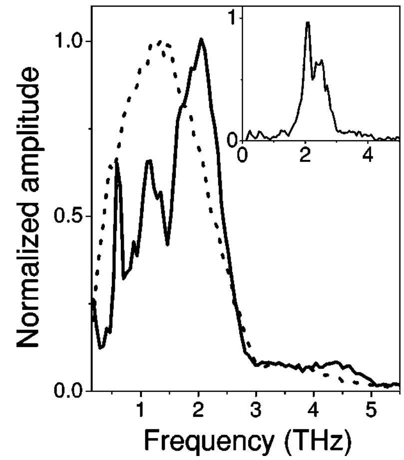

FIG. 2. Terahertz spectra normalized by their maxima. Dotted line, reference spectrum or instrumental response. Solid line, zero-order transmission spectrum through a grating of holes with dimensions $w=70\times 70$ μm, thickness $d=100$ μm, and lattice constant $a_0=400$ μm. The transmission spectrum of a grating with the same hole dimensions and lattice constant but with a thickness of $d=280$ μm is plotted in the inset. These spectra are obtained by Fourier transforming the time domain amplitudes of Fig. 1.

of Fig. 1 an image of a hole grating taken with an optical microscope is shown.

The choice of doped semiconductors for the excitation of SPP's at THz frequencies is justified by their permittivity, which is well described by the Drude model[23]

$$\epsilon(\omega)=\epsilon_\infty-\frac{\omega_p^2}{\omega^2+\tau^{-2}}+i\frac{\omega_p^2\tau^{-1}}{\omega(\omega^2+\tau^{-2})}, \qquad (1)$$

where ϵ_∞ is the high-frequency permittivity, τ is the average collision time of the electrons and $\omega_p=\sqrt{Ne^2/\epsilon_0 m^*}$ is the plasma frequency. The semiconductor doping concentration is given by N, while e is the fundamental charge, ϵ_0 is the vacuum permittivity, and m^* is the electron effective mass. With Eq. (1) it can be calculated that for n doped Si with $N=10^{18}$ cm^{-3}, $\epsilon'=-18.1$, and $\epsilon''=91.8$ at 1 THz. The relatively large value of ϵ'' in Si is due to its low electron mobility μ. The electron mobility is related to the average collision time of the electrons by $\mu=\tau e/m^*$. We have chosen silicon for our experiments for the following reasons: it can be obtained with ease, it is not toxic, and it can be easily structured. However, gratings made with semiconductors with high-mobility electrons, such as InSb, InAs, and GaAs, are expected to exhibit sharper resonances and larger enhancements in their THz transmission than the ones presented further in this article.

For the analysis of the transmission through the silicon gratings we used time domain THz spectroscopy.[23,24] This technique is based on using a femtosecond Ti:Sapphire laser beam split into two in order to excite and detect THz radiation. One of the beams is incident on a piece of InGaAs to photoexcite electrons from the valence band to the conduction band. The electrons and corresponding holes are then accelerated in the semiconductor depletion layer acting as dipoles that emit broadband THz pulses. This THz radiation is collected, guided with parabolic mirrors through the analyzed sample and the transmitted radiation focused onto a detection photoconductive antenna.[24] This antenna is based on an Auston switch,[25] which is a piece of semiconductor with a subpicosecond carrier lifetime, in our case low-temperature grown GaAs, placed in between two metal contacts. The second Ti:Sapphire beam is incident on this photoconductive switch, generating carriers. These carriers are driven by the THz electromagnetic field producing a measurable current which is proportional to the THz field amplitude incident on the antenna during the carrier lifetime. By varying the path length difference between the Ti:Sapphire beam used to generate the THz radiation and the beam employed to activate the Auston switch, the time dependent electromagnetic field is detected with subpicosecond resolution.

A typical THz pulse transmitted through air is plotted with a gray line in Fig. 1. This measurement is the instrumental response whose spectrum is plotted in Fig. 2 with a dotted line. The spectrum is obtained by calculating the Fourier transform of the pulse. The transmission through a grating of holes with a lattice constant of $a_0=400$ μm and a thickness of $d=280$ μm is plotted in the inset of Fig. 1. This grating was structured on a Si wafer without reducing its thickness in advance. As can be appreciated there is a large pulse dispersion which is related to the narrowing of the spectrum. The spectrum is plotted in the inset of Fig. 2. There is a pronounced peak around 2.1 THz. This frequency corresponds to the cutoff frequency of the square cavities with dimensions $w=70\times 70$ μm defined by the holes. Below the cutoff frequency, i.e., $\lambda>2w$, no propagating mode can be sustained by the cavity and the transmission drops to a very low value. However, this situation changes radically when the thickness of the grating is reduced. The black line in Fig.

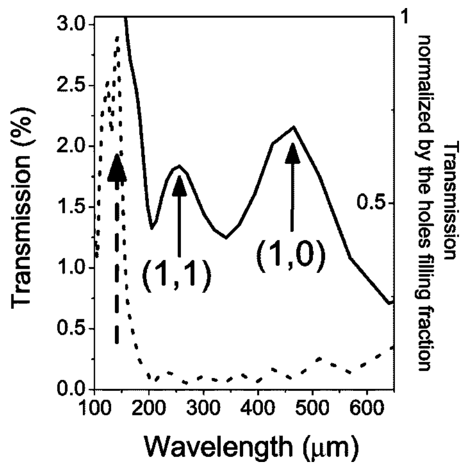

FIG. 3. Transmission efficiency through square gratings of holes with dimensions $w=70\times70$ μm. The lattice constant of both gratings is $a_0=400$ μm and the thickness are 280 μm (dotted line) and 100 μm (solid line). The black arrows indicate the (1,0) and (1,1) resonances. The dashed arrow marks the cutoff wavelength of the cavities defined by the square holes.

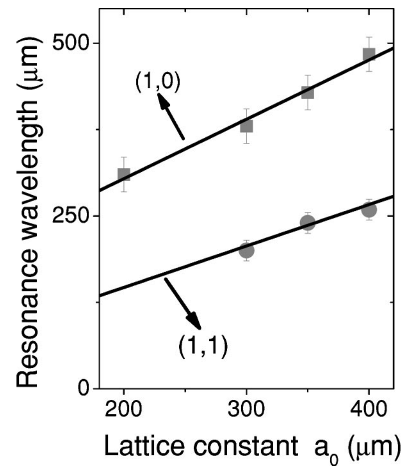

FIG. 4. Dependence of the resonance wavelength with the grating lattice constant. The squares correspond to the (1,0) resonance, while the circles are the (1,1) resonance. The lines are linear fits to the data.

1 represents the transmission of a THz pulse through a grating with $a_0=400$ μm and thickness $d=100$ μm. As can be appreciated in the spectrum of this measurement, plotted with a solid line in Fig. 2, there are spectral resonances at 0.64 and 1.15 THz. These frequencies correspond to vacuum wavelengths of 470 μm and 260 μm, i.e., wavelengths 6.7 and 3.7 larger than the hole dimensions. It is important to mention that the amplitude absorption length of Si with the doping concentration used in the experiments is $\simeq 6.5$ μm at THz frequencies. This absorption length is much smaller than the thickness of the wafers, being optically thick. No THz radiation is thus transmitted through the Si.

The effect of the hole depth in the subwavelength transmission has been experimentally investigated by Degiron *et al.*[7] Consistently with our measurements the transmission at the resonant wavelengths decreases with the hole depth or the wafer thickness. This is an expected result since the enhanced transmission at these wavelengths is associated to the tunneling through surface-plasmon polaritons formed on both sides of the grating.[14]

The zero-order transmissions normalized by the reference are plotted in Fig. 3. The dotted line corresponds to the sample with a thickness of 280 μm, while the solid one to the 100 μm sample. For the long-wavelength resonance ($\lambda=470$ μm), the transmission normalized by the area occupied by the holes or transmission efficiency reaches the extraordinarily large value of 70%. Classical diffraction theory predicts that the transmission through holes with dimensions $w\ll\lambda$ scales as $T\sim(w/\lambda)^4$.[26] Based on this theory and assuming that, due to the small absorption length of doped Si, only THz radiation incident on the holes might be transmitted, a transmission efficiency of roughly 1% is predicted. As in previous optical experiments,[1–7] the anomalous large transmission efficiency may be attributed to the resonant tunneling of surface-plasmon polaritons. In spite of the fact that the ratio $-\epsilon'/\epsilon''$ at THz frequencies of the Si used in these experiments ($-\epsilon'/\epsilon''\simeq 0.2$) is low compared to the same ratio for good metals at optical frequencies, a significant enhancement of the transmission is observed. As discussed above, this might be attributed to the effective permittivity introduced by the corrugation of the surface and to the small skin depth in doped Si.[21]

The wavelengths for the excitation of SPP's on square gratings with normally incident radiation are approximately given by[2]

$$\lambda_r=\frac{a_0}{\sqrt{l^2+m^2}}\sqrt{\frac{\epsilon_1\epsilon_2}{\epsilon_1+\epsilon_2}}, \qquad (2)$$

where a_0 is the lattice constant, ϵ_1 is the permittivity of the metal-like material, ϵ_2 is the permittivity of the dielectric, and l,m are integer mode indices. The $(l=1,m=0)$ and the (1,1) resonances are indicated with arrows in Fig. 3. It is important to point out that the polarization of the THz beam was linear along the x direction. Due to the procedure employed to define the grating in the Si wafers, the samples are asymmetric along their x and y directions, i.e., in each side of the samples there are lines patterned along only one direction. We checked the reproducibility of the measurements for different orientations of the samples relative to the polarization of the incident THz radiation. Within the experimental accuracy of our setup we did not see differences either in the resonant wavelengths or in the transmitted amplitudes. Therefore, the (1,0) and (0,1) resonances are assumed to be degenerate and we do not distinguish them further. Higher-order resonances than (1,1) were not observed.

To test the linear dependence of the resonance wavelength with the lattice constant [Eq. (2)], we measured the zero-order transmission through several samples with lattice constant in the range 200–400 μm. The resonance wavelength is plotted versus the lattice constant in Fig. 4; where the squares and circles correspond to the (1,0) and (1,1) resonances, respectively. The solid lines in Fig. 4 are linear fits to the experimental data. The slope of the fit to the (1,0) resonance has the value 0.87 ± 0.17, while for the (1,1) resonance the slope is 0.6 ± 0.2. As anticipated by Eq. (2), the variation of the resonance wavelength with the lattice constant is a factor of $\sqrt{2}$ larger for the (1,0) resonance than for the (1,1).

In conclusion, we have measured the enhanced transmission of THz radiation through gratings of subwavelength holes. This anomalous transmission is attributed to the resonant tunneling of surface-plasmons polaritons. Our gratings are structured in doped silicon. Due to the metallic behavior of doped semiconductors at THz frequencies, we demonstrate that it is possible to excite surface plasmon polaritons on these structures and to tunnel them through subwavelength holes. This observation paves the way for using subwavelength apertures for the development of sensitive THz imaging systems.

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