Optical control over transmission of terahertz radiation through arrays of sub-wavelength holes of varying size.

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Abstract

We modulate the transmission of terahertz radiation through periodic arrays of sub-wavelength holes in a metallic film by using pulses of visible-wavelength light to photo-excite the semiconducting substrate of the hole arrays. By varying the photo-doping level of the semiconductor we are able to switch off the resonant transmission of THz radiation through the array. By varying the size of the holes, we demonstrate the crucial role that surface modes play in the resonant transmission and ultimately in the photomodulation behavior of these structures. We demonstrate that the surface wave transmission mechanism can allow for very efficient optical modulation of radiation transmission.
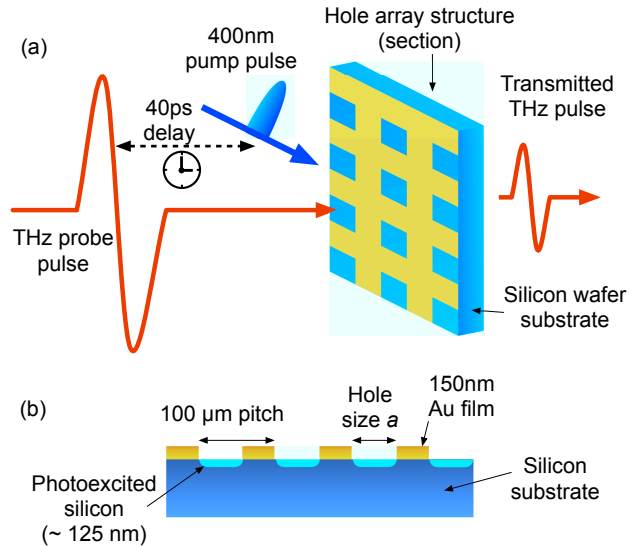
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FIG. 1: (Color online) (a) Diagram of the experimental measurement. A visible pump pulse with centre wavelength 400nm illuminates an array of holes in a gold film on substrate of silicon. 40 ps after the arrival of the pump pulse, a probe pulse in the THz range is transmitted through the hole array and subsequently detected in the far-field. (b) Side profile of the photoexcited structure, indicating the 100 μm array pitch and hole size a.

Photonic structures which incorporate some degree of dynamic control over their electromagnetic properties[1,2] are interesting for numerous reasons. Some structures have direct applications in proposed photonic devices; in others the dynamic control can provide direct evidence for transmission pathways and for the role of material properties in determining the behavior of a structure[3]. Manipulating material properties optically[4–10] is of particular interest, as changes to the structure can be made on the same time-scale as the transit of light pulses through the system.

One very fundamental photonic structure is an array of sub-wavelength holes perforated in a conducting screen. Such arrays can exhibit narrow transmission resonances[11] for wavelengths determined by the periodicity of the array - this is known as Extraordinary Optical Transmission, or EOT. The mechanisms underlying EOT in these arrays have been the subject of considerable debate[12–14], however consensus has gradually emerged that for many structures the transmission is mediated at least in part by electromagnetic surface modes at the interface between the perforated conducting screen and the dielectric layers by which it is bound[15,16].

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In this contribution we use pulses of visible light to modulate the transmission of terahertz (THz) radiation through periodic arrays of subwavelength holes in a metallic film fabricated at the interface of a substrate of crystalline silicon. By varying the photo-doping level of the silicon we are able to switch off EOT of THz radiation through the array. By varying the size of the holes we are able to explain the photomodulation effects in terms of the properties of the surface mode which mediates the enhanced transmission; in particular we can make a direct link between the lifetime of the surface mode and the magnitude of the photomodulation. We show that if we extend the surface mode lifetime by minimizing losses and reducing the hole size it is possible to attain photomodulation levels which are orders of magnitude greater than those found for a plain silicon surface.

The hole-array structure we shall consider in this work (Fig. 1) is formed from a 150 nm thick film of gold on a silicon substrate. The gold is perforated with a square lattice (pitch 100 μm) of square sub-wavelength holes - the holes have sides ranging in size from 25 to 85 μm. Previous works have shown[6,17–19] that such hole-array structures exhibit EOT at terahertz frequencies. The mechanism underlying the transmission can be considered as a Fano-type picture in which resonances arise from constructive interference between radiation which has transmitted straight through the holes, and radiation which has been transmitted after coupling to a surface mode on the metal-dielectric interface[16]. The frequencies of the EOT resonances ν_r are determined by the hole array lattice pitch d and the permittivity of the dielectric substrate, ε_d and are approximately given by:

$$\nu_r = \frac{\omega_r}{2\pi} \approx \frac{c\sqrt{i^2 + j^2}}{d\sqrt{\varepsilon_d}}, \tag{1}$$

where i and j are integers indicating the diffracted order coupling to the surface mode. We determine that the hole arrays under investigation have two EOT resonances in the measured frequency range of 0.4 to 1.4 THz, labeled as the $< 1, 0 >$ and $< 1, 1 >$. Both are due to surface modes on the interface between the silicon substrate and the gold film (modes on the opposing gold-air interface lie outside the spectral range of the incident terahertz pulse, above 3 THz). In this work we chiefly discuss the lowest-frequency ($< 1, 0 >$) resonance as changes to the relative coupling intensity between the higher order modes are complex and highly dependent on sample geometry[19]. The amplitudes and widths of the transmission resonances are determined by the lifetime of the surface mode mediating the transmission[20]. For a hole array made from lossless materials the lifetime of the surface mode is entirely determined

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by phase-retardation across the width of the holes; i.e. arrays with larger holes exhibit a shorter mode lifetime[19,20]. Through photoexcitation of the silicon surface in these samples one can effectively control this surface-mode mediated element of the EOT transmission, and alter the amplitude of the EOT resonances[6].

In Figure 1(a) we show a schematic of the experimental measurement. Two pulses (both arriving at a repetition rate of 1.05 kHz) separated by a 40 picosecond optical delay illuminate the hole array structure at the air-gold interface. The first pulse to arrive is a 100 fs, 400 nm pump pulse, which photo-excites the silicon exposed in the holes (Fig. 1(b)). The 400nm beam is expanded to a circle of 3 cm diameter to ensure that the region of photoexcitation is homogeneous across the 2 cm square sided sample area. The region of silicon photo-excited is very thin, as the penetration depth of the 400 nm light in the silicon is sub-micron[21]. The relaxation time for photo-excited charge carriers in silicon at room-temperature is of the order of microseconds[22] and so a 40 picosecond interval after the arrival of the pump pulse the silicon is in a steady, fully-photoexcited state i.e. we have essentially formed a thin film of extra charge carriers on the silicon interface underneath the holes. By fitting a Drude response to the measured permittivity of these carriers[23], we determine that our most intense photoexcitation beam produces a charge density in the silicon of approximately 2.8×10^{24} m^{-1}, corresponding to a plasma frequency of 30 THz. After the 40 ps interval the THz probe pulse arrives in a 1 cm diameter collimated beam. We detect the terahertz pulse which has transmitted through the sample in the far field using a terahertz spectrometer similar to the one described in Ref. 24. In this technique we measure the electric fields of the transmitted terahertz pulses as time-domain spectra[19]; these can be converted to transmission intensity spectra by taking the Fourier transform of the time domain pulses, squaring the field amplitude and normalizing by a reference spectrum.

In Fig. 2 we show transmission spectra taken through arrays of 45 μm holes for varying fluence of the 400 nm pump pulses. The two expected resonances ($< 1, 0 >$ and $< 1, 1 >$) are labelled. As we add an increasing fluence of 400 nm pulses we observe a distinct quenching of transmitted terahertz intensity at resonance. The quenching effect at the resonance peak is much higher than the quenching of the non-resonant transmission (which is dominant at lower frequencies). At the $< 1, 0 >$ resonance peak a pump fluence of 0.054 J/m^2 reduces the THz intensity by a factor of 0.69 - whereas at 0.6 THz, just below the resonance frequency, transmission intensity reduces by a factor of only 0.88. In order to evaluate this enhancement
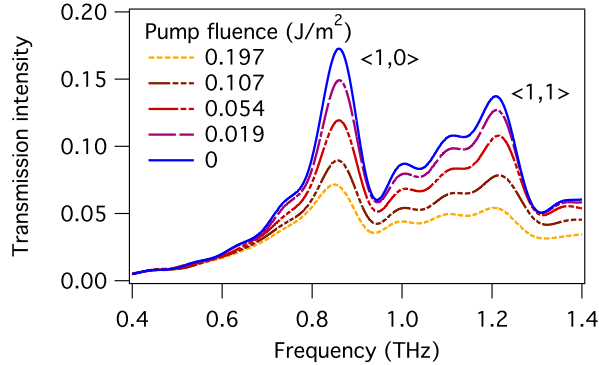
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FIG. 2: THz transmission spectra through arrays of 45 μm holes with various fluences of 400 nm pump beam. Photoexcitation quenches the EOT resonances, indicated as the $< 1, 0 >$ and $< 1, 1 >$ peaks

in photomodulation, we can define a photo-modulation ratio, P, as $P = (I_0 - I_{pm})/I_0$ where I_0 is the peak THz transmission intensity with no photo-excitation, and I_{pm} is the peak THz transmission intensity after 400 nm photo-excitation.

We compare these photomodulation levels directly in Fig. 3(a). In this figure we plot the photomodulation ratio P at 0.86 THz (the peak of the $< 1, 0 >$ resonance) as a function of the fluence of 400 nm pulses for various hole sizes. As a reference we also evaluate the photomodulation measured for a plain, unstructured silicon surface. We expect the plain silicon surface to exhibit the same amount of photomodulation as the non-resonant component of the hole array transmission, as in both cases the transmission pathways can be described by wave-vectors perpendicular to the interface. The hole array structures will introduce surface modes to the transmission - these surface modes have wave-vectors *parallel* to the gold silicon interface. For this reason we expect the transmission resonances to be more strongly modulated than the transmission through the plain silicon interface; this effect can be seen in Fig. 3(a) as the traces for the hole arrays all lie above that for the unstructured silicon.

In Fig. 3(b) we plot the modulation as a function of hole-size for various fluences, as well as for the unstructured silicon interface. We see a marked increase in the modulation as we decrease the hole size from 85 to 45 μm for all fluences, indicating that as we decrease the hole size the surface mode is predominating in the transmission. However, for the very smallest holes, the trend is reversed and the resonant transmission for the 25 and 35 μm
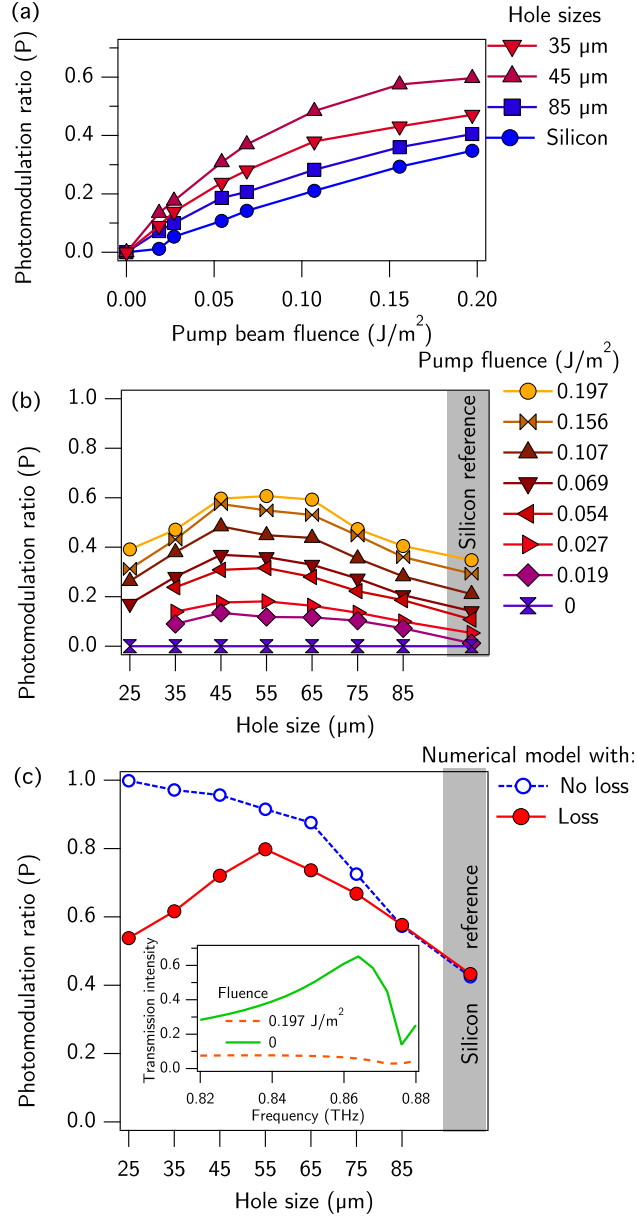
FIG. 3: (Color online) (a) Photomodulation versus fluence of 400 nm pump pulses for three sizes of hole and a reference surface of silicon.(b) Experimentally measured photomodulation vs. hole size for various fluence of 400 nm pump pulses. For the 25 μm holes it was not possible to measure photomodulation for the lowest fluences due to the low level of transmitted THz signal. (c) Numerically modeled photomodulation of the THz transmission at resonance as a function of hole-size at a 400 nm pump fluence of 0.197 J/m^2, with and without loss in the silicon substrate. INSET: Modeled transmission spectra through 55 μm holes in a lossless substrate, with and without photoexcitation.

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holes is clearly less strongly modulated than for the 45 μm holes. In a lossless hole array, one might expect that the photomodulation effect would be greatly enhanced for arrays of very small holes, as the lifetime of the surface mode is increased. Indeed, in Fig. 3(c) we plot the results of finite element numerical modeling[26] of hole arrays on a lossless silicon substrate (blue dashed line). This simple, lossless model predicts that P increases monotonically upon decreasing the hole size; example transmission spectra shown as an inset in Fig. 3(c) indicate that we see a similar resonance-quenching effect upon photoexcitation of the silicon substrate as we have observed in the experimental measurement. The non-monotonic trend of photomodulation with hole size seen in our experiment is due to intrinsic losses within our silicon substrate; a low concentration of impurity charge carriers in the crystalline silicon contribute an imaginary component to the permittivity of the substrate, which reduces the surface mode lifetime. In the 25 and 35 μm holes the surface mode lifetime is not limited by phase-retardation across the holes, but instead by absorption in the silicon substrate - this in turn limits the interaction of the surface modes with the photo-excited silicon. By introducing an imaginary component to the dielectric constant of the silicon substrate in our model of $0.56i$ at 0.85 THz (determined by phase-resolved THz transmission measurements through the silicon substrate) we can accurately reproduce the experimental results as the solid red line in Fig. 3(c). The model incorporating loss exhibits the non-monotonic trend in photomodulation with hole size seen in the experiment, and further demonstrates the role of surface mode lifetime in determining the modulation. The modelled modulation for the given fluence is actually slightly higher than that measured in experiment; this is because we do not fully recover the narrow mode width for transmission through the smallest holes - the instrumental frequency resolution of the terahertz spectrometer is limited by reflections within the silicon substrate[19].

Our results suggest that if one could limit the intrinsic losses in an array of very small holes fabricated on a semiconductor, the photomodulation effect could become extremely efficient. Our modeling in Fig. 3(c) indicates that for an array of 25 μm holes on a lossless silicon substrate a fluence of less than 0.2 J/m^2 will produce a photomodulation ratio of near unity. This photomodulation ratio corresponds to the intensity (I_0/I_{pm}) changing by a factor of 600, compared to a factor of only 1.5 for the unstructured plain silicon surface. If we compare this to other reports of photo-modulation of terahertz in literature using silicon with similar densities of photoexcited charge carriers, a silicon-based photonic crystal structure has been

shown[10] to modulate terahertz intensity by a factor of approximately 12, and a silicon-based waveguide structure[25] gives an intensity change of 1.4 under a continuous-wave excitation. In our lossy experimental system, the maximum intensity change attained (with the 55 μm hole array) is a factor of 2.6, very comparable with other measured photomodulation measurements in hole array structures[4,6]. In order to approach the modelled factor of 600 one would need to reduce the levels of scattering and loss in the system - this can be achieved by using ultra high-purity semiconductor substrates and cooling to cryogenic temperatures[19]. Additionally, the photoexcited carrier lifetime in silicon is relatively long: for modulation by a pseudo continuous wave light source this long carrier lifetime is useful, as one can build up a high carrier density with a relatively weak light source. However, in pulsed applications the long lifetime imposes a maximum repetition rate of switching. This constraint could be avoided by using direct band gap semiconductors such as GaAs instead of silicon[8].

In conclusion, we have shown how photomodulation of the EOT in our hole array structures is governed by the effects of surface mode propagation. By adding a metal hole array structure to the surface of a silicon substrate we are able to enhance the response of the silicon to photoexcitation. In particular we find that when surface mode lifetime is limited (such as by intrinsic loss in the substrate) the photomodulation enhancement is similarly limited. However our modelling shows that by following the strategies for loss-reduction and increasing the surface mode lifetime extremely high efficiencies for optical modulation could be achieved using this scheme. Such efficient optical modulators could find applications as non-linear switches in optical circuitry and related systems.

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