Nonlinear Terahertz Generation in Semiconductor Metasurfaces

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***Abstract*—We demonstrate ultra-thin semiconductor metasurfaces for generation of THz pulses. By investigating the dependence of the THz amplitude and phase on excitation field polarization and crystal orientation, we deduce that the underlying THz emission mechanism in metasurfaces differs from bulk semiconductor wafers with second order nonlinearity playing a dominant role. The metasurface enables control of the THz phase and can therefore be used to spatially structure the THz emitted field. We use this effect to design and demonstrate a metasurface which simultaneously emits and focusses THz pulses.**

I. Introduction

WHILST many semiconductors emit terahertz (THz) pulses when excited with fs near infrared (NIR) pulses, only a few select materials have the physical properties required to be useful THz sources. However, metasurfaces (MS) provide an alternative route of optimizing the THz generation process, as they enable the engineering of a material's optical properties through the structural geometry. MSs can therefore be used to not only enhance THz generation from a wide range of materials, but also directly engineer the emitted THz field.

Plasmonic MSs have been shown to generate THz radiation by enhancing an otherwise weak optical rectification process at metallic surfaces [1], and have even been used to spatially and temporally control the emitted THz field [2]. However, their efficiencies are still low in comparison to more established schemes such as InAs and ZnTe crystals. In principle, all-dielectric semiconductor MSs can take advantage of a wider variety of generation mechanisms - both photocurrent and nonlinear - which can both be tuned with MS design.

Here, we investigate various semiconductor metasurfaces for THz generation. Firstly, we design a GaAs MS and explore the dominant underlying generation mechanisms. We show that despite the drastically reduced volume, the MS can be used to generate THz pulses with comparable amplitude and bandwidth to generation from much thicker bulk crystals. Interestingly, the emitted THz field polarity differs from the THz field from bulk wafers, demonstrating that different emission mechanisms are dominant in the MS.

Following this, we use the fact that the THz field polarity can be directly tuned by the MS design to experimentally demonstrate an MS which is able to emit and focus the THz field.

This work lays the foundations for efficient, versatile and tunable MS THz emitters that could be easily integrated into THz systems and therefore highly beneficial for a wide range of THz spectroscopy and imaging applications.

II. Results

Firstly, we design a MS based on GaAs, which is able to support a wide variety of THz generation mechanisms [3]. The MS is designed to maximize absorption of NIR light when excited at a 45° angle (Fig. 1a,b), by exciting Mie modes in the MS unit cell which are degenerate and critically coupled to the incident field [4]. This enables near-perfect absorption at the pump wavelength, which enhances photocurrent and nonlinear shift currents for THz generation [5], which both rely on efficient photoexcitation of charge carriers.

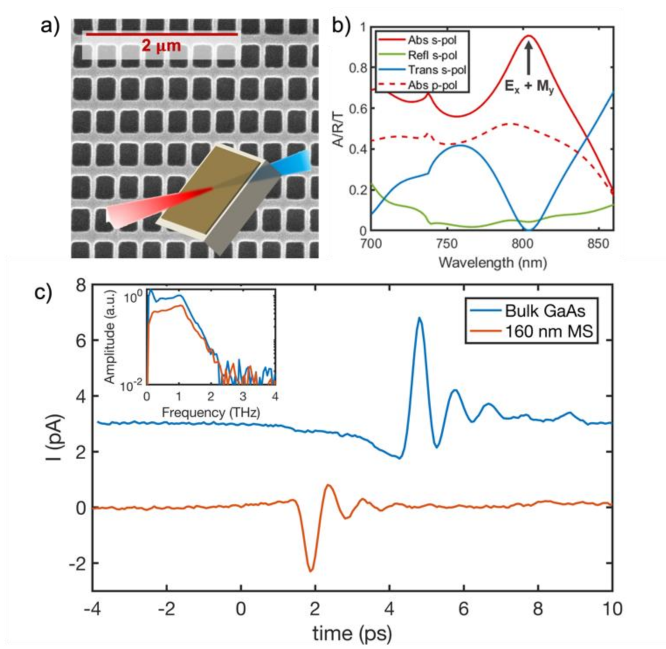

Fig. 1. (a) SEM of metasurface. Inset: schematic of experimental geometry showing near infra-red light (red) illuminating the MS, which produces THz pulses (blue); (b) Simulated optical spectra of highly absorbing MS (MS oriented at 45° to incident field excitation); (c) Time domain THz waveforms measured from the 160 nm thick MS and a bulk GaAs crystal. Inset: Fourier spectra of the THz pulses.

When measuring the THz emission from the MS (Fig.1c), we observed that the emission amplitude is comparable to bulk GaAs wafer despite being only 160 nm thick. However the THz polarity is reversed, suggesting an alternative underlying emission mechanism. To understand this further, we map the THz amplitude and polarity dependence on the incident field polarization (Fig. 2a). The THz emission is strongly dependent on the incident polarization, indicating that in contrast to bulk crystals where photocurrent mechanisms are cited as the main source of THz emission, the THz emission in a GaAs MS is largely due to second order nonlinearity. When excited above the bandgap, nonlinearity in GaAs is caused by shift currents [6], which are therefore enhanced by the high absorption of the metasurface.

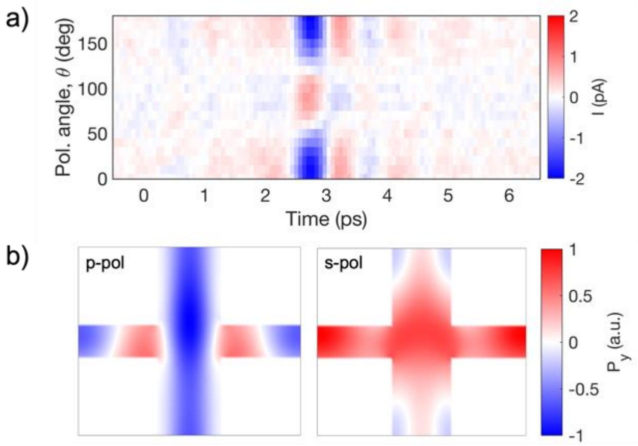

Fig. 2. (a) Map of THz time-domain waveforms measured at varying incident polarization angles; (b) Numerically calculated volume nonlinear polarization in the MS unit cell for s- and p- polarized incident light.

We calculate the nonlinear polarization induced in the MS within the unit cell for s- and p-polarized incident light, using the simulated electric fields in the MS and second order susceptibility tensor for bulk GaAs. In Fig. 2c areas of both positive and negative induced polarization can be seen in each case, indicating that important consideration must be taken when designing the metasurface, so that nonlinear polarizations add constructively to give maximum possible THz field strength.

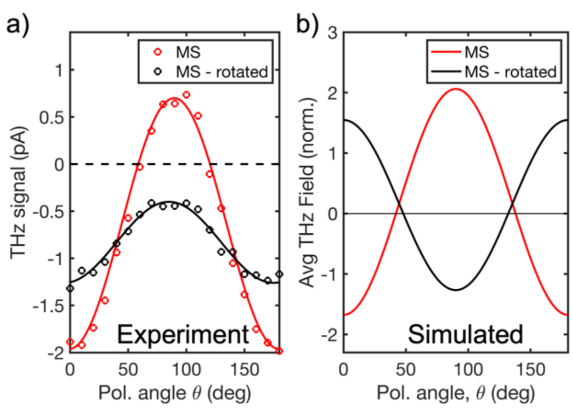

Fig. 3. (a) Measured (symbols) peak-to-peak THz pulse amplitude for varying incident excitation polarization angle for two orientations of the MS; (b) Calculated THz pulse amplitude from volume second order nonlinearity for varying incident excitation polarization angle for two orientations of the MS.

In order to determine whether our experimental results have the same dependence on polarity as expected from our calculation of volume nonlinearity, we sum the nonlinear polarization over the entire MS area and use this to calculate the expected THz field dependence on incident field polarization and MS orientation (Fig. 3). Whilst we find a good agreement with the experimental data for one orientation of the MS (red line), we also find that the calculated volume nonlinearity does not show the same dependence on MS orientation as the THz field measured from the MS. This result, combined with our investigation of the THz emission from unpatterned GaAs layers [3], allows us to conclude that a significant proportion of the THz field is generated at the MS interfaces, where the nonlinear properties of the material are altered due to the abrupt change in crystal structure.

Having discovered that the nonlinearity in the GaAs MS dominates THz emission rather than photocurrent effects, and that the THz field polarity can be altered by the MS, we can then investigate whether this is also the case for other materials which are known to emit THz generation of larger amplitude than GaAs. In addition, the tunability of phase through MS orientation and design can allow spatial structuring of the emitted field. As an example, by alternating MS regions that give opposite THz polarity, a phase gradient can be induced, resulting in an overall focusing of the emitted THz field [6].

III. Conclusion

In conclusion, we have demonstrated THz emission from semiconductor metasurfaces and investigated the THz field dependence on metasurface design, orientation and incident field polarization. We have shown that MSs be used to produce THz emission much more efficiently than bulk wafers, and development of the metasurface design to ensure that generated THz fields add constructively could increase the THz amplitude further. Furthermore, MSs can also be used to control the emitted THz pulse phase allowing for structured THz field emission. Semiconductor metasurfaces therefore have the potential to provide a new, versatile platform for THz generation, where the THz field strength and polarity can be tailored through intelligent design of the metasurface.

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