Terahertz Generation from GaAs Metasurfaces: Role of Surface Nonlinearity

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Abstract: We show that a GaAs metasurface can generate THz radiation with comparable efficiency to a bulk GaAs crystal. We attribute the enhanced generation to second order nonlinearity with the surface making a strong contribution.

1. Introduction

Metasurfaces have enabled the strong enhancement of nonlinear frequency conversion processes. Surface nonlinearity in particular has been shown to significantly influence second harmonic generation in dielectric metasurfaces and nanostructures [1,2]. Recently, nonlinear plasmonic metasurfaces were developed for generation of terahertz (THz) pulses [3]. However, the efficiency of THz generation in plasmonic resonators was found to be relatively low. In contrast, bulk semiconductors can generate broadband terahertz (THz) pulses upon ultrafast photoexcitation with a much higher efficiency through a number of processes, including optical rectification, transient photocurrents and shift currents. ZnTe and InAs crystals are routinely used as reliable THz emitters for THz spectroscopy and imaging applications. Semiconductor metasurfaces therefore offer an opportunity to enhance and control the efficiency of these generation process through engineering the metasurface's optical properties. So far, generation of THz radiation using metasurfaces made of III-V semiconductors remains largely unexplored.

Here, we demonstrate that ultra-thin GaAs metasurfaces can produce THz radiation with comparable efficiency to bulk GaAs crystals. Moreover, we identify that a large contribution to the generated THz field comes from second order surface nonlinearity. To our knowledge, this is the first demonstration of THz generation from an all-dielectric metasurface, and the first observation of THz generation due to surface nonlinearities. Our results suggest that semiconductor metasurfaces could enable ultra-thin, tailored THz emitters for numerous sensing, spectroscopy and imaging applications and provide an ideal platform for investigating the underlying physical mechanisms of THz generation.

2. Results

GaAs allows us to access a wide range of THz generation mechanisms. In particular, THz generation in photoexcited optically-thick GaAs can occur as a result of ultrafast current transients driven by built-in surface fields [4] and charge density gradients (i.e. the photo-Dember effect) [5], as well as shift currents, which were found to be the leading second order nonlinearity mechanism for above bandgap excitation [6]. All of the above-mentioned mechanisms require efficient charge carrier generation. Therefore, we design a 160 nm thick GaAs metasurface that achieves almost complete absorption of photoexcitation at 780 nm using a concept called degenerate critical coupling [7]. We previously developed a GaAs metasurface based on this concept for normal incidence illumination [8], and here we develop a design with degenerate critical coupling for the incident angle of 45° - the angle commonly used for THz generation. A scanning electron microscope image of this metasurface is shown in Fig. 1.

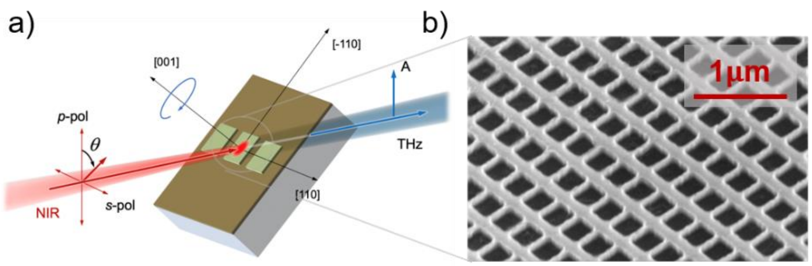

Figure 1. a) Schematic of THz generation setup: metasurface crystal axes are shown in black, near-infrared (NIR) excitation polarization is shown in red and the polarization of detected THz field is shown by 'A'. b) 'Close-up' scanning electron microscope image of the metasurface.

When the metasurface is excited by NIR femtosecond pulses in the configuration shown in Fig. 1a, we observe generation of broadband THz pulses. A time-domain waveform of the pulses is measured in transmission using a photoconductive antenna detector. Figure 2a, b shows the THz pulses and spectra measured from the metasurface compared to THz pulses generated from an optically-thick GaAs crystal. Despite being just 160 nm thick, the metasurface generates THz radiation with comparable amplitude and a similar spectral bandwidth.

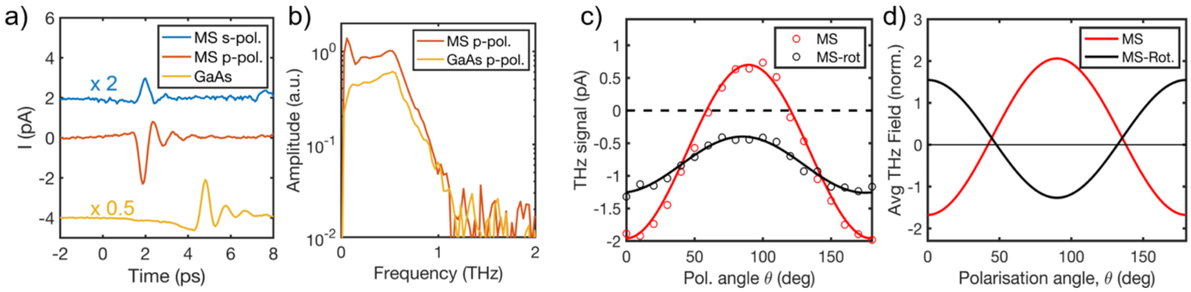

Figure 2. a) THz time-domain waveforms measured from the metasurface (MS) and a bulk GaAs crystal (GaAs) b) Amplitude spectra obtained by Fourier transform of the waveforms of corresponding color in (a). c) Experimentally measured peak-to-peak THz amplitude as a function of excitation polarization (0°,180° = p-polarization, 90° = s-polarization) for two different rotations, 0° and 90°, of the metasurface. d) Numerically calculated second-order nonlinearity contribution to THz field amplitude normalized to the numerically calculated THz field from an unpatterned 160nm thick GaAs layer. Volume nonlinearity alone is insufficient to explain experimental observations.

To determine the origin of THz emission from the metasurface, we measure the THz amplitude dependence on the excitation polarization (Fig. 2c) for two different rotations, 0° and 90°, of the metasurface around their normal axis. A strong dependence on excitation polarization is observed, with maximum THz field amplitude measured for the p-polarization. The pulse polarity is reversed when the excitation polarization is changed to s-polarized (Fig. 2a). This behavior rules out photocurrent effects as the dominant mechanism of THz generation. Further analysis allows us to conclude that second order nonlinearity is most important for THz generation in the metasurface with the surface playing a particularly significant role. The origin of nonlinearity is shift currents – the spatial charge transfer as a result of electron excitation from the valence to conduction band.

3. Conclusion

We show that GaAs metasurfaces can produce THz radiation with comparable efficiency to thick GaAs crystals. While the conventional generation mechanisms play a less important role in the metasurface, we associate a significant portion of THz generation with surface nonlinearity. Studies of alternative metasurface designs can help develop a model of surface nonlinearity and harness it for versatile THz emitters.

4. Acknowledgements

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5. References

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