SAND2023-07357C

Photoconductive Metasurfaces for Near-Field Terahertz Sources and Detectors

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ABSTRACT

Aperture near-field microscopy and spectroscopy (a-SNOM) enables the direct experimental investigation of subwavelength-sized resonators by sampling highly confined local evanescent fields on the sample surface. Despite its success, the versatility and applicability of a-SNOM is limited by the sensitivity of the aperture probe, as well as the power and versatility of THz sources used to excite samples. Recently, perfectly absorbing photoconductive metasurfaces have been integrated into THz photoconductive antenna detectors, enhancing their efficiency and enabling high signal-to-noise ratio THz detection at significantly reduced optical pump powers. Here, we discuss how this technology can be applied to aperture near-field probes to improve both the sensitivity and potentially spatial resolution of a-SNOM systems. In addition, we explore the application of photoconductive metasurfaces also as near-field THz sources, providing the possibility of tailoring the beam profile, polarity and phase of THz excitation. Photoconductive metasurfaces therefore have the potential to broaden the application scope of aperture near-field microscopy to samples and material systems which currently require improved spatial resolution, signal-to-noise ratio, or more complex excitation conditions.

Keywords: Near-field, microscopy, aperture, metasurface, photoconductive, terahertz, spectroscopy

1. INTRODUCTION

Near-field microscopy and spectroscopy has been instrumental in many scientific advances in the terahertz (THz) range. Aperture near-field microscopy (a-SNOM) is a certain type of near-field scheme which uses a THz probe with a metallic aperture to detect evanescent fields on a sample surface with micron-scale resolution [1,2]. In particular, this enables the measurement of individual, subwavelength-sized THz resonators, which have low radiation efficiency, making them extremely challenging to measure using standard far-field techniques. Combined with THz time-domain spectroscopy (THz-TDS), a-SNOM is therefore a powerful technique which can retrieve both amplitude and phase information about local electromagnetic fields. A-SNOM has been used to study a wide variety of material systems – from measuring the evolution of surface waves on carbon microfibers [3] and metasurface arrays [4], to measuring phonon-plasmon coupling in topological insulators [5].

Since near-field methods require sensing of highly confined and often weak electromagnetic fields from subwavelength-sized elements, the poor detection efficiency and low source power of THz systems often limit the extent of near-field measurements. Recently, a new method which uses all-dielectric photoconductive metasurfaces as the active region was developed to enhance the efficiency of THz sources and detectors. Metasurfaces allow us to simultaneously miniaturise THz photoconductive devices, while also tailoring them to have desired optical and electronic properties. Here, we discuss how these all-dielectric photoconductive metasurfaces are an ideal candidate to improve the performance of THz sources and detectors specifically for the purpose of near-field microscopy. By replacing photoconductive elements in THz devices with ultra-thin metasurfaces, these benefits can be harnessed to improve the efficiency and sensitivity of near-field systems with the goal of opening THz near-field microscopy to the study of a broader range of potential applications and material systems.

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

2. NEAR-FIELD APERTURE PROBES

To understand the potential for photoconductive metasurfaces in near-field devices, it is necessary to explain how aperture probes work and what currently limits their performance. The aperture near-field probe consists of a photoconductive antenna (PCA) integrated with a metallic subwavelength-sized aperture (Fig. 1a) [2,6]. For pulsed operation used in TDS, a femtosecond near-infrared (NIR) pulse incident on the far side of the probe excites charge carriers in the photoconductive region. The THz field that couples through the aperture on the front side then drives the carriers to metallic antennae for detection. The near-field probe therefore requires the same characteristics necessary for efficient and sensitive THz detection as in regular PCAs, such as high NIR photon-to-charge carrier conversion efficiency, high contrast between conductive and non-conductive states, and short carrier lifetimes for large detection bandwidth [7].

However, there are also additional requirements specific to the near-field operation of the probe that must be considered. Firstly, the THz field which couples through the aperture decreases quickly with the aperture size [8]. This means that the presence of the aperture drastically reduces the THz field that is able to reach photoconductive region, making the requirements for sensitive THz PCA detection even more stringent. Secondly, evanescent field components that couple through the aperture decrease in intensity with distance from the aperture plane [2]. Since charge carriers are generated by the optical beam on the far (antennae) side of the detector, this constrains the thickness of the photoconductive layer. These issues not only limit the sensitivity if a-SNOM systems but also the spatial resolution as it is often necessary to use apertures no smaller than 5- 10 µm to ensure sufficient THz signal is detected. Finally, the near-field probe must be positioned in very close proximity to the sample, so it is necessary that there is no NIR transmission through the probe that could interfere with the sample.

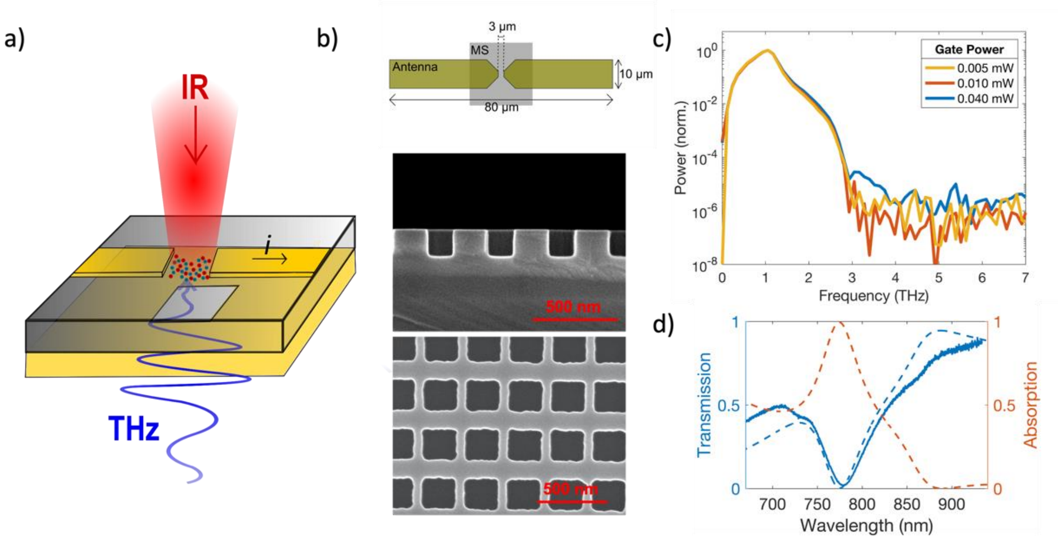

Figure 1. a) Schematic of a near-field aperture probe. b) Schematic of THz PCA detector with an integrated photoconductive metasurface, and SEM images of the metasurface. c) Power spectral density measured with a metasurface-integrated photoconductive antenna detector. High dynamic range and bandwidth up to 3 THz is observed with NIR gating powers as low as 5uW. d) Simulated (dashed) and experimentally measured (solid) optical properties of the photoconductive metasurface, demonstrating near-zero transmission at the NIR gating pulse wavelength. [11]

3. PHOTOCONDUCITVE METASURFACE DETECTORS

Despite significant work on enhancing improving photoconductive detectors [9,10], the efficiency of a typical PCA detector is still relatively low; approximately 10^9 NIR photons are required for one electron of detected photocurrent [11]. However, recently it was demonstrated that by replacing the photoconductive region in PCAs with an ultra-thin photoconductive LT-GaAs metasurface (Fig. 1b), the efficiency of PCAs can be improved by several orders of magnitude, enabling high dynamic range (10^6) THz detection with NIR light on the µW level (Fig.1c) [11,12]. This is possible as the metasurface achieves 100% absorption of NIR light through the excitation of two degenerate critical coupling of two Mie modes supported by the metasurface at the NIR wavelength [13] (Fig. 1d). The photon-to-charge carrier conversion efficiency is therefore maximised while also maintaining a very high dark resistance (80 GΩ) due to the reduced material cross-section of the metasurface.

The reduced thickness of the metasurface (~ 200 nm) compared to standard PCAs with bulk LT-GaAs photoconductive regions (~ 2 µm) makes them readily applicable to near field aperture probes, where thin photoconductive regions are imperative for sensitive THz detection. Furthermore, the application of photoconductive metasurfaces could not only improve the sensitivity and efficiency of aperture probes, but also increase the spatial resolution of a-SNOM systems, as the improved sensitivity to THz fields could enable the use of even smaller aperture sizes.

4. METASURFACE THZ SOURCES FOR NEAR-FIELD SYSTEMS

In addition to THz detectors, semiconductor metasurfaces also have the potential to be a new, versatile platform for THz generation where the THz field strength, polarity and spatial beam structure can be tailored through intelligent design of the metasurface [14–16]. Recently, we have demonstrated that both GaAs and InAs metasurfaces can be used to generate THz radiation [14,17]. In particular, an InAs metasurface can generate THz radiation via optical rectification with greater efficiency than a ZnTe crystal. The metasurface can be used to tune THz pulse polarity and amplitude, and this functionality was used to demonstrate InAs metalens with a focal length of 5mm [14]. In near-field systems this is a particularly attractive prospect, as ultra-thin metasurfaces which do not require any extra focusing optics could be readily integrated into complex near-field systems, and tailoring the THz beam profile could enable more efficient excitation of subwavelength samples and the investigation of more complex resonator designs which require specific spatial beam profiles [18].

5. CONCLUSION

We examine how recent developments in semiconductor metasurfaces can be used to enhance the efficiency, sensitivity and versatility of near-field systems. Firstly, it is discussed how advances in photoconductive metasurfaces for THz detection could be incorporated into THz near-field aperture probes to improve their sensitivity and spatial resolution. Secondly, the application of semiconductor metasurfaces to near-field THz sources is explored, where metasurfaces can generate THz radiation while simultaneously spatially controlling the THz beam excitation. Advances in metasurface technology therefore could open doors to more in-depth near-field exploration of subwavelength-sized structures and material systems which either require unconventional, tailored excitation conditions, or where current near-field systems lack sensitivity.

6. REFERENCES

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Acknowledgements

This work was supported by the EPSRC and by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering. L.L.H. was supported by the EPSRC (EP/P021859/1, EP/L015455/1, EP/T517793/1). Metasurface fabrication was performed at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. This article describes objective technical results and analysis. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.