Sensitivity and Noise in THz Photoconductive Metasurface Detectors

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***Abstract*— Photoconductive antenna THz detectors based on highly absorbing LT-GaAs metasurfaces enable high sensitivity and high signal-to-noise ratio (> 10^6) at optical gate powers as low as 5 μW. By investigating the dependence of detector performance on optical gate power, we compare several metasurface detectors with standard PCAs and develop a general model for quantifying the sensitivity and optimal gate power for detector operation. We also show that the LT-GaAs metasurface can even enhance sub bandgap absorption, enabling the use of these detectors in telecom wavelength systems.**

I. Introduction

Recently introduced metasurface photoconductive antennas (PCAs) - where the photoconductive region is replaced by an LT-GaAs metasurface (MS) - have improved performance of THz photoconductive detectors [1]. The MS enhances the photon-to-charge carrier conversion efficiency by enabling full absorption of the near-infrared (NIR) gate pulse in a thin photoconductive channel through degenerate critical coupling to Mie modes [1,2]. This design maximizes the ON/OFF switching contrast [3], and the low gate power requirement enables a wider range of applications, such as detector arrays for THz imaging systems.

Here, we investigate how the MS affects the detection sensitivity and noise in PCA detectors. We analyze both the THz field-induced photocurrent and photocurrent noise at different levels of gate power for several MS detectors. Using a general current saturation model, we compare the performance of our MS detectors to standard PCAs. Finally, we evaluate the smallest THz field that can be measured at different levels of the gate power. This analysis shows that, contrary to common use of PCAs at gating powers which give the highest possible THz field, the best detector performance is at powers near the saturation power of the detector. Moreover, further increasing the gating power reduces the detector sensitivity.

Furthermore, we also consider GaAs photoconductive metasurfaces for use with excitation at telecom wavelengths (1.55 μm). In this case, the metasurface serves to enhance two-step photon absorption at wavelengths below the GaAs bandgap, enabling the operation of LT-GaAs PCAs.

Our results not only demonstrate the improved detection efficiency and sensitivity of MS detectors in comparison to standard PCAs, but also provide a systematic framework which can be used to compare the performance of PCA detectors of different designs.

II. Results

Figure 1a,b shows a LT-GaAs MS integrated into a photoconductive detector. Two degenerate in-plane electric dipole modes are excited in the metasurface. These two dipole modes have opposite symmetries to each other with respect to the metasurface plane, and therefore can be used to satisfy the degenerate critical coupling condition [2] and enable full absorption of NIR light at 780 nm (Fig. 1c inset). Figure 1c shows the THz waveform and spectrum measured with this MS detector. A high signal-to-noise ratio is achieved at gate powers down to 5 μW – several orders of magnitude lower than the gate power used for typical PCAs. This ultra-low noise performance of the detector is a result of the MS design that enables very high dark resistance (~80 GΩ) due to the subwavelength thickness (160 nm) and small fill factor of the photoconductive region compared to bulk GaAs.

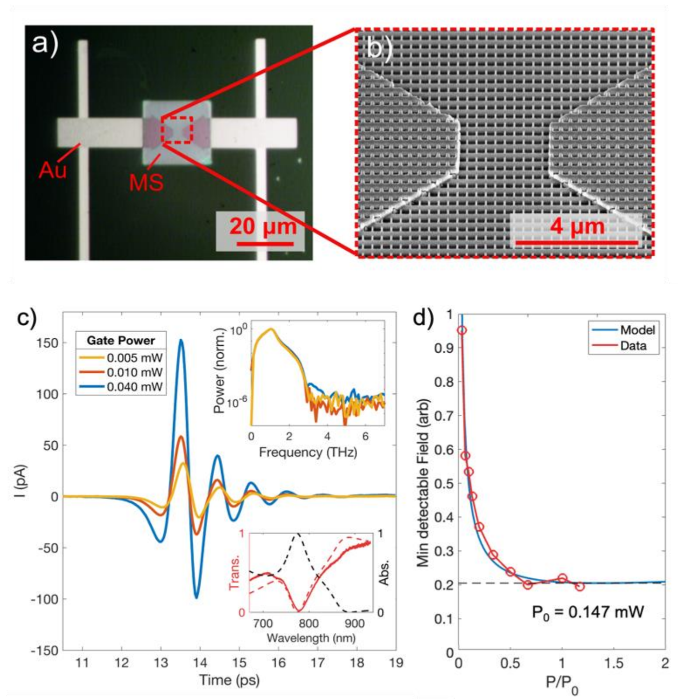

Fig. 1. THz detector with integrated MS: (a) microscope and (b) SEM images: the 160 nm thick MS designed for perfect absorption at 800 nm. (c) THz time-domain waveforms measured with MS PCA detector at varying gating power (gating wavelength 800nm). Inset top: Power spectral density of measured waveforms. SNR > 10^6 is achieved at powers down to 5 μW. Inset bottom: Simulated (dashed) absorption and transmission and measured (solid) transmission spectra of MS. (d) Minimum detectable THz field as a function of optical gating power, normalised to detector saturation power, P_0 (gating wavelength 800nm). We estimate the lowest detectable field for our MS detector at 100 μW gate power is 0.2 V/m.

To determine the optimum gate power for operation of metasurface detectors, we measure the THz peak-to-peak photocurrent dependence on the gate power and find that the

MS detectors follow the universal photocurrent saturation behavior that has been commonly reported for unstructured PCA detectors and sources [3]. However, for the MS detectors the saturation power is an order of magnitude lower (0.147 mW) [3].

We also investigate the detector noise dependence on gating power, which is dominated by a combination of Johnson noise, Shot noise and noise from the input amplifier [3]. We define an optimal gate power at which the smallest detectable THz field can be measured, which we estimate to be approximately 0.2 V/m for our detector. Interestingly, the highest sensitivity is observed for gate powers in the range of the saturation power, and for much higher gate powers the sensitivity of the PCA degrades, highlighting the importance of considering the optimal operating power of PCA detectors, rather than using gate powers that simply give the highest peak THz field.

We then use the same concept of degenerate critical coupling of modes to design a different metasurface which enhances two-step photon absorption below the GaAs bandgap [4]. This enables the use of LT-GaAs PCAs with compact, robust fiber lasers that exist at telecom wavelengths (1550 nm). Usually, PCAs operating at this wavelength require photoconductive materials with a reduced bandgap such as InGaAs. However, InGaAs has low resistivity, resulting in poor detector performance. As a result, ion-implantation or complex material heterostructures must be used to enable InGaAs for ultrafast detection [5]. Instead, by using a metasurface to enhance the normally weak two-step absorption process via mid-gap states (Fig. 2a), we can benefit from the superior ultrafast material properties of LT-GaAs, whilst also permitting PCA operation at 1550 nm.

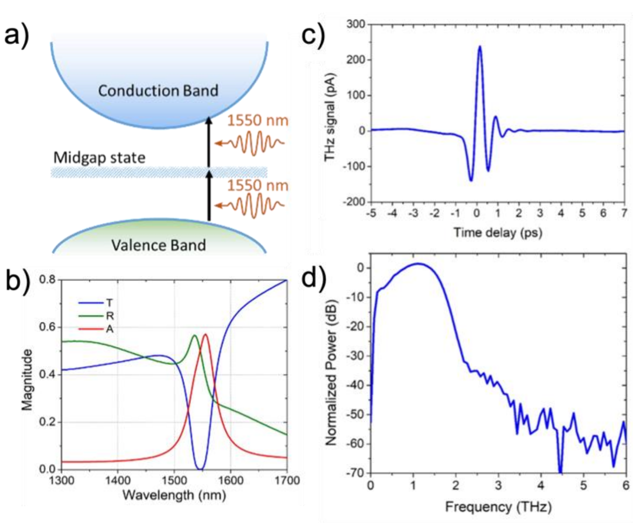

Fig. 2. THz detection at sub-bandgap wavelengths: (a) schematic showing two-step photon absorption via mid-gap states in LT-GaAs. This usually weak absorption process is enhanced by the MS. (b) Simulated optical properties of MS (T- transmission, R- reflection, A – absorption). LT-GaAs is simulated with an extinction coefficient of κ=0.01 at 1550 nm. (c) THz time-domain waveform measured with PCA detector at a gating wavelength of 1550nm and gating power of 17 mW. d) Power spectral density of measured waveform in (c). SNR ~ 10^6 and bandwidth up to 4 THz is achieved.

Whilst degenerate critical coupling can in theory enable 100% absorption, due to the low intrinsic material absorption of LT-GaAs at 1550 nm, perfect absorption results in an impractically narrow absorption linewidth. We therefore modify the metasurface design to increase the radiative losses, thus resulting in a maximum absorption of ~ 60%, and a linewidth which covers the full bandwidth of the pump laser (Fig. 2b).

The Figure 2c shows the THz waveform from an InAs source measured with our MS detector operating at 1550 nm. Remarkably, despite the low intrinsic absorption of the material as well as the subwavelength thickness of the MS photoconductive region, the detector performance is comparable to conventional LT-GaAs PCAs operating at 800 nm. The power spectral density (shown in Fig. 2d) shows a peak signal-to-noise of 60 dB and a wide bandwidth up to 4 THz. Due to the two-step photon absorption process, the THz photocurrent shows a super-linear and sub-quadratic dependence on gating power, and does not saturate for optical gating powers up to 17 mW. As for the MS PCAs operating at 800 nm, this impressive performance is a consequence of the low dark current of the MS, due to its drastically reduced photoconductive cross-section and the high resistivity of LT-GaAs.

III. Conclusion

In summary, we have investigated in detail the detection performance of PCAs based on photoconductive LT-GaAs metasurfaces. The low dark current and improved sensitivity of these detectors allows for optimal operation at substantially lower powers than conventional PCA detectors. Moreover, the use of degenerate modes for high absorption enables the enhancement of sub-bandgap absorption at 1550 nm, allowing the integration of our MS PCA detectors with mature, fiber-based technologies at telecom wavelengths.

References

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Acknowledgement

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering. LLH was supported by the EPSRC (EP/P021859/1, EP/L015455/1, EP/T517793/1). Metasurface fabrication and characterization were 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.