THz Detectors with Photoconductive Metasurfaces Operating at Microwatt Gate Power Levels

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Abstract: We demonstrate terahertz (THz) detectors enabling high signal-to-noise ratio photoconductive detection at gate powers as low as 5μW. This is achieved by integrating a photoconductive metasurface, which enhances the detector efficiency and sensitivity.

1. Introduction

Terahertz (THz) Time-Domain Spectroscopy (TDS) is a highly sensitive technique which underpins spectroscopy and imaging research at THz frequencies. Many TDS systems rely on photoconductive antennas (PCAs) for THz detection owing to their robust room-temperature operation. However, despite their wide application, their efficiency has not been improved significantly. For a typical PCA, approximately 10^9 – 10^{10} near infrared gate photons are required to generate a single electron of detector photocurrent [1]. This poor efficiency limits the range of PCA applications, for example, as detector arrays in imaging systems. Recently, we introduced perfectly absorbing photoconductive metasurfaces as an alternative to the bulk photoconductive region in PCA detectors [2–4]. The metasurface can increase optical photon-to-charge carrier conversion efficiency by means of full absorption of the gating pulse, whilst also allowing engineering of the electronic properties of the photoconductive channel to improve the detector sensitivity.

Here, we demonstrate the effect of ultra-thin LT-GaAs metasurfaces on performance of THz PCA detectors. We show that the combination of metasurface-enabled efficient absorption of the near-IR gating pulse and a highly reduced photoconductive volume leads to the most efficient PCA switching properties demonstrated to date. As a result, high signal-to-noise ratio (10^6) is achieved at gate powers as low as 5 μW, and the optimal gate power for achieving the highest detector sensitivity is one order-of-magnitude lower compared to standard PCAs.

2. Results

The metasurface integrated into the PCA detector (shown in Fig. 1a) is only 160 nm thick and it has an area fill factor of 54%, yet it enables close to 100% absorption of the gate beam at 780 nm through degenerate critical coupling to the electric dipole and magnetic dipole modes supported in each meta-atom [5]. By adjusting the size and periodicity of the meta-atoms, these modes can be tuned in the range from 700 nm to 840 nm to match the wavelength of the near-IR gate beam [3]. Conductive channels within the metasurface enable the transfer of charge carriers through the photoconductive layer to the THz antenna. The PCA shows a linear I-V behavior with a dark resistance of 80 GΩ. This extremely high dark resistance is due to the greatly reduced cross-section of the photoconductive channels. Two dipole arms with a 3μm gap are deposited directly on top of the metasurface (Fig.1a), and the device is attached to a sapphire substrate using epoxy.

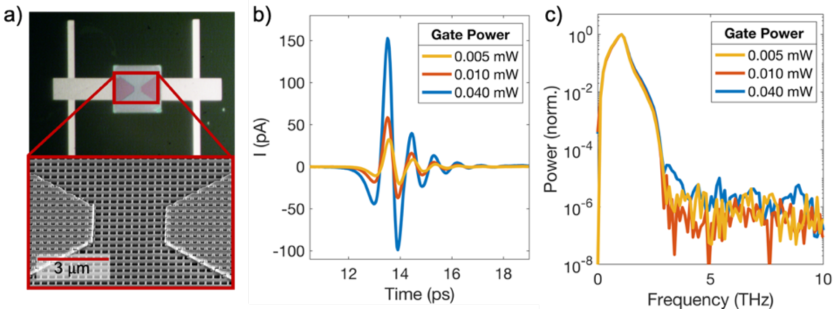

Figure 1. a) Microscope image of THz detector and SEM of central metasurface region. b) Time-domain waveforms measured with metasurface detector at low gate powers c) Power spectral density (PSD) obtained by the Fourier transform of measured waveforms in (b). [7]

THz pulse detection is tested in a standard THz-TDS system driven by a Ti:Sapphire laser (80 MHz repetition rate; pulse duration: 100 fs; central wavelength: 780 nm). A 1mm-thick zinc telluride crystal is used to generate broadband THz pulses. Figure 1b,c shows THz pulse waveforms detected by the metasurface PCA using low gating powers: 5, 10 and 40 μW, and the corresponding power spectral densities. Remarkably, even for the lowest gating power of 5 μW - ~3 orders of magnitude lower than the power used for standard PCAs - the THz waveform shows an excellent dynamic range of ~10^6.

The excellent performance of the detector with relatively low gate power demonstrates an improved photon-to-charge carrier conversion efficiency. To compare this detector to other PCA detectors, in Fig. 2a we provide gate power saturation characteristics (dependence of the THz photocurrent on the gating power) for three different metasurface detector designs. All the detectors follow the universal saturation behavior: $I(P) \propto (P/(P + P_0))\, E_{THz}$, where P denotes the gating power, P_0 is the saturation power parameter and E_{THz} is the THz field [6]. However, the saturation power, P_0 for the metasurface detectors is one order of magnitude smaller than those reported for standard PCAs [7].

The effect of the gate power on sensitivity to the THz field is illustrated in Fig. 2b. As the gating power increases, the minimum detectable THz field falls sharply at first, before levelling off around the saturation power, P_0. For the metasurface detector in Fig. 1, the optimal gating power is around 0.14 mW and we estimate the lowest detectable field at 1 THz to be 0.2 V/m [7]. Gating powers much higher than the saturation power are actually detrimental to the detector performance due to an increase in noise.

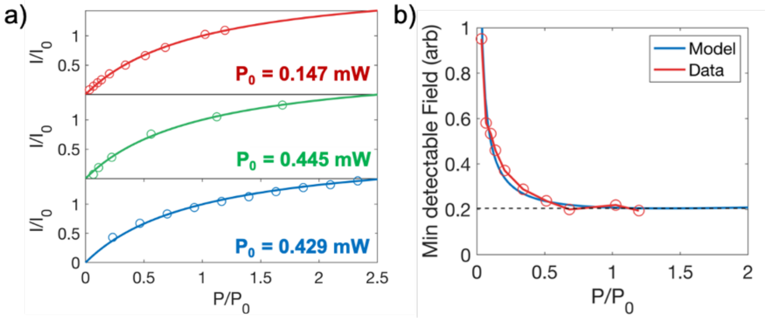

Figure 2. (a) Gate power saturation behavior: normalized detector photocurrent as a function of normalized gating power. Saturation power, P_0, is found by fitting the saturation function $I(P) = A(P/(P + P_0))$, where A = const. The normalized photocurrent $I_0 = I(P_0)$. Red curve shows the saturation behavior of metasurface detector in Fig. 1, green and blue curves describe other metasurface detectors in [2] and [4] respectively. b) Minimum detectable THz field as a function of gate power: experiment (red) and model (blue) [7].

3. Conclusion

In conclusion, we demonstrate metasurface-based PCA THz detectors which achieve high signal-to-noise ratio (10^6) at gate powers as low as 5μW due to the highly efficient conversion of photons to charge carriers and the very high dark resistance of the metasurface detector. The minimum detectable THz field is reached at gating powers close to the saturation power of the detector – which is an order of magnitude lower for metasurface detectors compared to standard PCAs. The combination of high sensitivity and low gate power requirement could open up metasurface PCA detectors to new applications, such as detector arrays for imaging.

4. Acknowledgements

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5. References

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