Perfectly-absorbing photoconductive metasurfaces for THz applications

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Abstract— **Ultrafast switching of photoconductivity lays in the foundation of many terahertz (THz) technologies, including photoconductive THz emitters and detectors. This process however often is far from being efficient, leading to the long-standing problem of poor efficiency in THz sources and detectors. We will discuss how the recently developed concepts of all-dielectric metasurfaces can improve efficiency of the ultrafast switches, overcoming material limitations, reducing the thickness of the photoconductive region and lowering optical power requirements for THz devices. We will consider two types of perfectly absorbing metasurfaces compatible with the photoconductive switch architecture and discuss performance of THz detectors with integrated metasurfaces. We will show that optical power level required for optimum operation for these THz detectors is more than one order of magnitude lower in comparison to devices without metasufaces. We will also discuss a wider range of THz devices where such metasurfaces offer routes for improving their efficiency.**

I. INTRODUCTION

ULTRAFAST switching of photoconductivity enables essential terahertz (THz) technologies, including emitters and detectors of THz pulses. There are three key requirements for the ultrafast switch: efficient photo generation of charge carriers, sub-picosecond carrier lifetime and high contrast between the ON and OFF states. Satisfying all three requirements in one material however has been a challenge. Photoexcited carriers are able to travel only a short distance (<100 nm) within the photoconductor during the short lifetime. Typically, only photocarriers generated within a distance of 50-100 nm from the detector electrodes contribute to the photocurrent. Meanwhile only a small fraction (<10%) of incident photons are absorbed within that distance. The top 100 nm of GaAs for example absorbs ~7% of incident photons at 800 nm. To mitigate this problem and enhance the efficiency of photoconductive devices, field-concentrating nanostructures have been explored, both for detection and emission of THz radiation [1]. Concentrating the optical fields close to the contacts or close to the surface and employing enhanced light absorption schemes has led to increased optical photon-to-charge carrier conversion efficiency.

However, together with improving field concentration, plasmonic nanostructures also introduce Ohmic losses within metallic elements. Our own investigations of THz detectors with plasmonic antennas showed that Ohmic losses can amount to one half of incident light [2], limiting the efficiency gain and lowering device damage threshold.

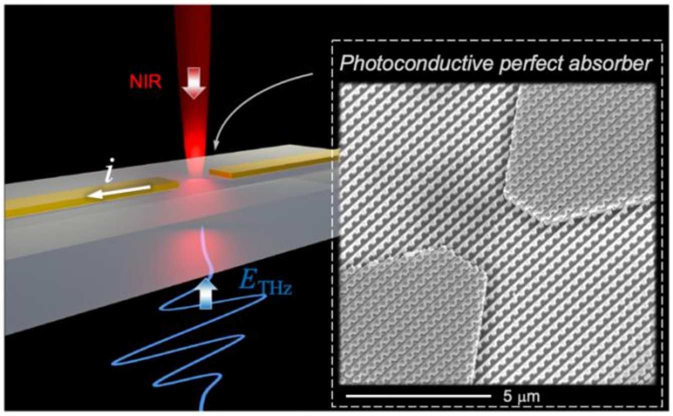

Fig 1. Illustration of a photoconductive THz detector with integrated perfectly-absorbing photoconductive metasurface. The inset shows an SEM image of a 200 nm thick metasurface fabricated from LT GaAs in the gap of the THz antenna.

All-dielectric photoconductive metasurfaces can also improve the photon-to-charge conversion efficiency [3], however without Ohmic losses. In fact, complete optical absorption of incident photons (perfect absorption) can be achieved in a nanostructured photoconductive region of only ~200 nm thick [4,5]. Furthermore, such metasurfaces can be engineered to adjust electronic properties of the photoconductive channel, and they can be fabricated using typical ultrafast photoconductors, such as low temperature (LT) grown GaAs. Integration of such metasurfaces into THz devices, for example a photoconductive THz detector (Fig. 1), enables excellent detector performance with only a fraction of required optical power.

II. PERFECT ABSORPTION IN ALL-DIELECTRIC METASURFACES

A number of different concepts for perfect absorption of light have been proposed in recent years. Here we will focus on all-dielectric metasurface designs, which can be realized using LT GaAs and which also provide a photoconductive channel. First, we consider a scheme, which relies on excitation of two degenerate modes of opposite symmetry. If a metasurface supports odd and even modes (with respect to the metasurface plane), these modes are degenerate and critically coupled, then perfect absorption of incident light can be realized.

Figure 2a illustrates such a metasurface supporting two magnetic dipole (MD) modes oriented within and perpendicular to the metasurface plane to satisfy the symmetry requirement [4]. The metasurfaces consists of cubic resonators connected into a network with thin bars. The MD modes exhibit strong confinement within the resonator, enabling a thin metasurface (~200 nm) capable of complete absorption of excitation at 800 nm. The bars enable charge carrier conduction and provide required asymmetry for excitation of the out-of-plane MD mode. By exciting this structure with linearly polarized light, both the in-plane MD mode and the out-of-plane MD mode can be excited. It is also possible to design a perfectly absorbing metasurface using both the MD and electric dipole mode (ED).

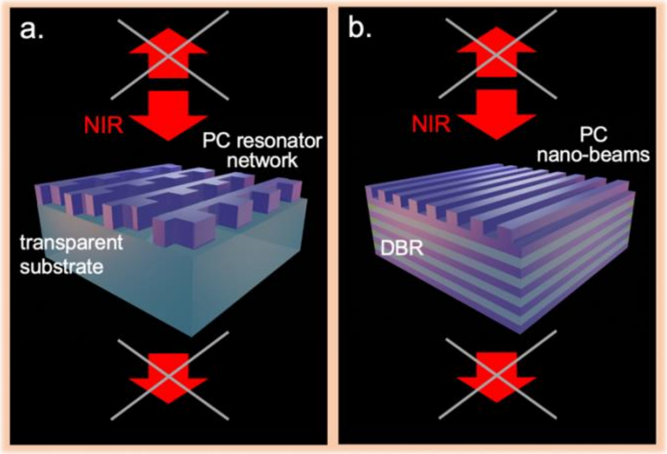

Fig 1. All-dielectric perfect absorbers for GaAs as the photoconductive (PC) material (purple): (a) PC resonator network supporting two MD modes; and (b) PC nanobeams on DBR. Both designs provide continuous charge transport channels [3].

The second design is shown in Fig. 2b, where enhanced absorption is achieved through manipulation of the amplitude and phase of waves reflected from the nanostructured top surface and the distributed Bragg reflector (DBR) below it. The top-surface structure also provides a PC channel. An intuitive understanding of this scheme can be gained by considering reflection from the nanostructured surface and the DBR. The nanobeams provide a narrow-band reflection peak corresponding to a resonance with spatial field distribution similar to the in-plane MD mode [5], whereas the DBR provides uniform reflectivity within a wider stopband. By controlling the size of the nanobeams, their density and position with respect to the DBR, one can minimize reflection through destructive interference and enhance absorption of the incident wave [5].

While the efficiency of absorption for both metasurfaces depends sensitively on the structure dimensions, we have developed step-by-step prescriptive approaches for designing perfectly absorbing metasurfaces at a desired wavelength of operation [6,7].

III.Photoconductive THz detectors with Integrated Metasurfaces

Both metasurfaces shown in Fig. 2 were integrated into THz photoconductive detectors and tested using a THz time-domain spectroscopy system. Figure 3 shows an example of THz pulse time-domain waveform detected by a device with integrated metasurface. It produces a noticeably higher photocurrent output compared to conventional THz detectors for an average excitation power of only $P_g = 100$ µW [4].

Figure 3 also shows the root-mean squared (RMS) noise of the photocurrent measured at a frequency of 2.7 kHz. The noise increases linearly at optical excitation powers above 100 µW, indicating that the main noise source is fluctuations of the laser power. Even at this low level of optical excitation, we begin observing the onset of absorption saturation: the THz-field induced peak photocurrent increases sub-linearly with the average optical excitation power. The maximum signal to noise ratio (SNR) is achieved at $P_g = 100$ µW, which is approximately one order of magnitude lower than what is observed for similar THz PC detectors without the metasurface.

The metasurface channel also exhibits very high dark resistance (~50 GOhm) in comparison to detectors based on unstructured LT GaAs layers (~1 GOhm). The higher resistance leads to a higher ON/OFF switching contrast (>10^7) and better SNR at low optical excitation powers. Therefore, the low optical excitation power required for the optimum SNR performance is due to (1) the efficient optical absorption and (2) the high dark resistance of the metasurface channel.

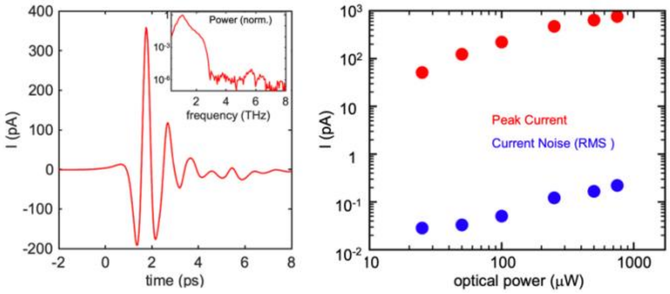

Fig 2. THz PC metasurface detector performance.

IV. Summary

Structuring photoconductive elements in ultrafast switches as perfectly absorbing metasurfaces offers a promising approach for improving their efficiency. These metasurfaces enable efficient optical absorption of photons, reduction of the photoconductive volume and increase in the ON/OFF switching contrast, leading to device operation at significantly lower optical power levels with excellent noise performance. This approach can revolutionize the photoconductive switch technology by opening doors to a wider range of photoconductive materials and by enabling applications deemed impractical previously, such as THz PC detector arrays.

Acknowledgments

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