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Resonant Fully Dielectric Metasurfaces for Ultrafast Terahertz Pulse Generation

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Abstract. In the framework of optical frequency conversion, metasurfaces have elevated the potential for effective interfacial nonlinear coefficients through various modes of field localization. For the generation of pulsed ultrafast terahertz (THz) signals, metasurfaces present a viable alternative in the domain of surface-scalable sources driven by low-power oscillators (using nJ pulses). However, recent innovations have predominantly relied on surface plasmons (metals) and, more broadly, on excitations within non-transparency windows—conditions that typically impose limitations on applications and the choice of platforms. Here, we demonstrate the utilization of a fully-dielectric, fully transparent semiconductor that exploits surface-nano-structure-mediated resonances alongside its inherent quadratic nonlinear response. Our system exhibits a remarkable 40-fold efficiency enhancement in comparison to the non-decorated substrate.

1 Introduction

Optical metasurfaces, the two-dimensional counterpart of metamaterials, have emerged as a compelling area of research in photonics. In general terms, metasurfaces are densely engineered surfaces and are often composed of arrays of subwavelength structures where the field is manipulated by different local field-matter processes. Research has been motivated by the promise of manipulating light in novel fashions, thereby opening up new avenues for optical functionalities [1]. Within the framework of the nonlinear frequency conversion, i.e. the generation of new optical frequencies via a nonlinear field-matter interaction, metasurfaces are assuming a quite intriguing pivotal role, as they offer a unique platform to enhance the nonlinear optical processes, overcoming the limitations posed by conventional nonlinear materials such as phase-matching constraints and low conversion efficiencies [2–4]. The investigation of these concepts within the terahertz (THz) frequency spectrum is quite recent. General research on terahertz light, which occupies the 0.1 to 10 THz band of the electromagnetic spectrum, is fuelled by fundamental and practical ramifications in fields as different as biological imaging art restoration and telecommunications. The nonlinear generation of terahertz pulses from ultrafast optical sources is indeed standard in the field [5–7] and it is historically considered a seminal achievement enabling the modern terahertz research area. However, in relevant domains, the lack of efficient area-scalable thin emitters is certainly a fundamental and practical limit responsible, for example, of resolution limits of novel near-field imaging systems [8–11]. Among the platforms proposed in the community, metal-based metasurfaces (operating on surface plasmons mechanism) offer a relatively strong nonlinear response boosted by local field enhancement without the several challenges related to the typical velocity matching condition required in bulk generation. Metal high ohmic losses at optical frequencies are the typical drawback that affects nonlinear conversion efficiencies. Recently, terahertz generation from above-bandgap excited semiconductor metasurfaces has been demonstrated [12] in absorption regime. The generation exceeds the one from the native substrate, usually driven by a combination of different surface phenomena, e.g. surface quadratic nonlinearities, carrier drift and photo-Dember processes [13] and the bulk nonlinear response. Drawing insights from purely theoretical studies on THz generation from individual all-dielectric nano antennas dominated by Mie resonances in the infrared, here we present a fully transparent AlGaAs metasurfaces tailored for pulsed terahertz generation from an extended system, which similarly employs dielectrics to mitigate conversion losses.

2 Results and discussion

This work demonstrates broadband all-dielectric metasurfaces for efficient, customizable terahertz pulse generation. The proposed structure comprises cylindrical semiconductor nano-resonators based on the AlGaAs/GaAs platform. We examined three different designs characterized by a bidimensional array of nanocylinders with an elliptical cross section, each with distinct ellipticities Dx:Dy, where Dx and Dy are the axis of the elliptical base Fig. 1b displays an inset for the 2:1.3, 1:1, and 2:2.3 ellipticity metasurfaces. Specifically, the 1:1 design has a circular base with a 190nm radius, 2:1.3

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has dimensions of 384nm by 207nm, and 2:2.3 measures 380nm by 437nm. The period of the bidimensional array is 750nm.

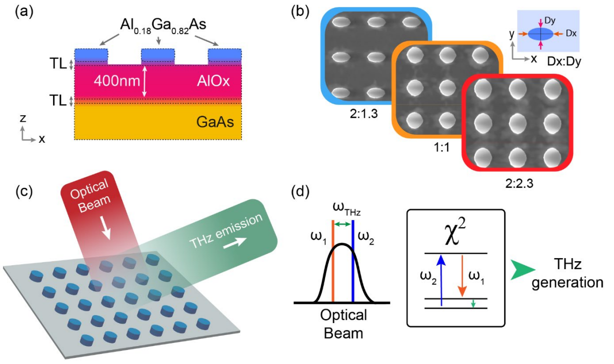

Fig. 1. Terahertz generation mechanism in resonant dielectric metasurfaces. (a) Sketch of the metasurface's composition: AlGaAs elements over a 400nm-thick AlOx substrate. TL – transition layers 90nm-thick. (b) SEM insets of the metasurfaces spatial distribution (Full SEM images available in Supplementary Figure 1). The metasurfaces are named after the ratio Dx:Dy. The 1:1 design has a circular base with a 190nm radius, 2:1.3 has dimensions of 384nm by 207nm, and 2:2.3 measures 380nm by 437nm. (c) Conceptual sketch of the THz generation process (d) Diagram of the intra-pulse optical rectification process.

Through optimisation of the metasurface design, a significant 40-fold enhancement in terahertz emission efficiency is achieved compared to the bare substrate. Intriguing, beyond the efficiency, the structure enables form of control over the emitted terahertz radiation characteristics. By tailoring the shape and dimensions of the nano-cylinder elliptical cross-section, the amplitude and the phase profile of the resulting terahertz pulses can be changed. The structures enable manipulation of the terahertz phase by merely tuning the optical excitation wavelength. This peculiar capacity for spatio-temporal structuring of the terahertz wavefront at a planar nanophotonic interface could empower different type applications. These include ultrafast terahertz beam steering, wireless communication, computational imaging, and spectroscopy. More broadly, the approach highlights the potential of all-dielectric metasurfaces.

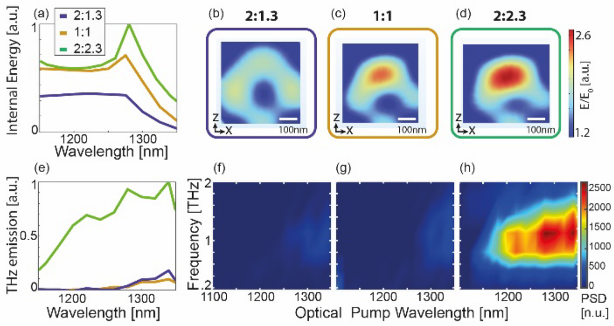

Fig. 2. Study on terahertz emission from the dielectric metasurfaces. (a) Simulated total internal energy for the different metamaterials, (b-d) The simulated field enhancement inside the meta-atoms that form the different metasurfaces 2:1.3, 1:1, 2:2.3 respectively. E_0 represents the amplitude of the incident field. (e) THz experimental contribution from the nanoparticles as a function of the optical pump wavelength. (f-h) THz experimental emission from the 2:1.3, 1:1, 2:2.3 metasurfaces respectively, results are show in in the frequency domain, where PSD is power spectral density. Note (e-h) are obtained subtracting the substrate contribution.

Our theoretical and experimental endeavours will be presented in detail [14].

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