Photo-Induced Coded-Aperture Terahertz Imaging using Mesa-Array Structures for Approaching Subwavelength Resolution

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***Abstract*— We present a novel and unique solution for approaching subwavelength-resolution terahertz (THz) photo-induced coded-aperture imaging (PI-CAI) by utilizing micromachined mesa-array structures. In this approach, photo-induced free carriers are confined inside each mesa, facilitating much more refined photopatterns for achieving subwavelength spatial resolution. Mesa-array structures with a unit cell dimension of 105 µm × 105 µm, and a trench width of 7 µm were fabricated and tested. An average of ~11 dB modulation depth was obtained in the frequency range of 740-750 GHz under a light intensity of only 4 W/cm^2. Initial imaging experiments have been performed, and the results meet the expectations quite well.**

I. Introduction

In recent years, terahertz (THz) frequency regime has attracted increasing interest due to its emerging applications in medical imaging [1], security screening [2], and radio astronomy [3]. THz imaging has been extensively explored for the above applications utilizing array imagers (e.g., focal plane arrays) [4] and single-element imagers [5] (e.g., scanning probe microscopy). However, these prior approaches either require large-scale arrays of detectors or raster mechanical scanning, leading to increased system complexity and limited imaging performance (e.g., speed and resolution).

To overcome the above problems, coded-aperture imaging (CAI) technique [6] which is promising for realizing both system simplicity (e.g., a single-element detector) and high performance (e.g., high SNR and speed) has been proposed and demonstrated. Schottky diodes [7] and graphene modulators [8] have been reported to realize CAI aperture masks (for spatial modulation of THz waves). However, restricted by biasing circuitry, pixel sizes cannot be further scaled down, resulting in low imaging resolution and limited mask reconfigurability. An alternative approach is to employ photo-induced (PI) free carriers in semiconductors to generate reconfigurable CAI masks without the need for additional, complicated circuit prepatterning or device fabrication/integration [9]. However, due to lateral diffusion of PI free carriers, the achievable spatial resolution is limited, restricting its applications for imaging requiring higher resolution.

In this paper, we report a novel and unique solution for approaching subwavelength-resolution THz photo-induced coded-aperture imaging (PI-CAI) by utilizing micromachined mesa-array structures. The proposed structures utilize a two-dimensional array of semi-isolated mesas with lateral dimension much smaller than the wavelength. By confining PI free carriers inside each mesa, much more refined photopatterns and consequently much smaller mask pixels can be achieved to potentially demonstrate subwavelength imaging resolution. Si mesa-array structures with a unit cell dimension of 105 µm × 105 µm, and a trench width of 7 µm were fabricated and tested. An average modulation depth of ~ 11 dB was obtained in the frequency range of 740-750 GHz under a light intensity of ~ 4 W/cm^2. Initial imaging experiments were performed at 740 GHz, and the results meet the expectations quite well. More advanced THz imaging will soon be performed for demonstrating subwavelength resolution using the proposed mesa-array approach.

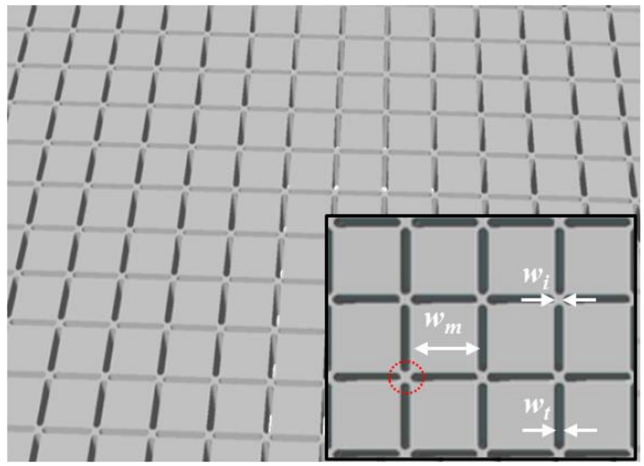

Fig. 1. Schematic drawing of mesa-array structures and zoom-in detail. The red dotted circle indicates a w_i-wide small connecting island at the corners of adjacent mesas (with a mesa width of w_m, and a trench width of w_t).

II. Optical Terahertz spatial modulation of Mesa-array structures

It has been demonstrated from our previous work that the THz transmittance of a semiconductor can be spatially modulated by changing the incident light intensity and the illuminated light pattern [10]. This spatially-resolved optical modulation (SROM) method could be applied to realize tunable and reconfigurable THz devices such as modulators, variable attenuators, and filters. However, due to lateral diffusion in naturally-existing semiconductors, the achievable spatial resolution of the resulted photopatterns from SROM is limited, restricting the implementation of tunable/reconfigurable devices in the THz regime [11].

To overcome this problem, we propose a novel optical approach to improve the spatial resolution based on micromachined mesa-array structures. As shown in Fig. 1, this structure consists of a two-dimensional array of subwavelength (e.g., w_m = 10 µm, much smaller than the lateral diffusion

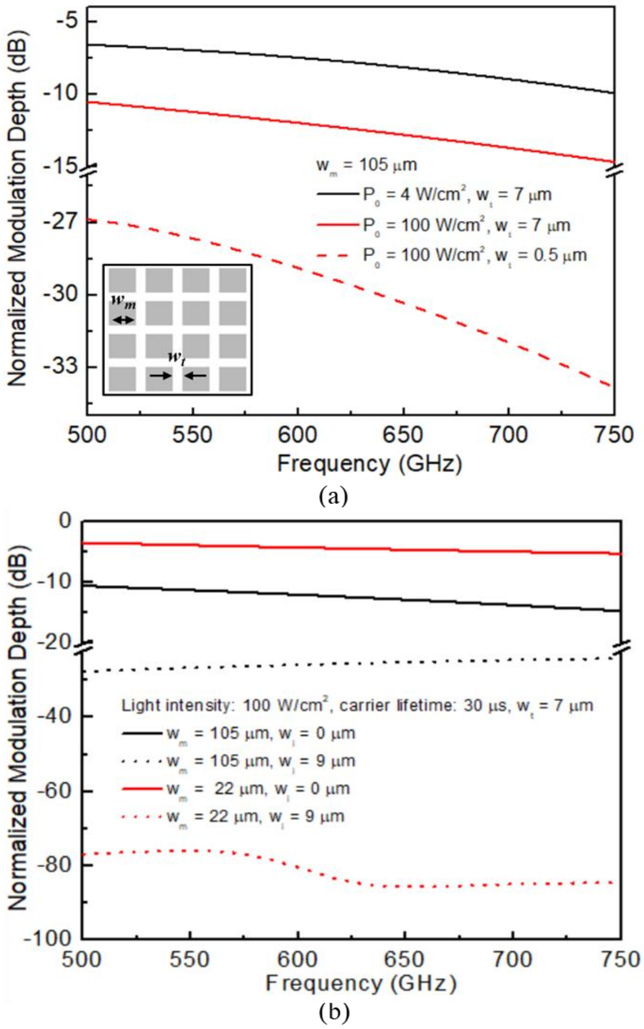

Fig. 2. (a) Optical spatial modulation depth of Si mesa-array structures with w_m = 105 µm, h = 50 µm, w_i = 0 (without connecting islands), and different w_t (i.e., 7 µm, and 0.5 µm). (b) The modulation depth comparisons for mesa-array structures (w_t = 7 µm, h = 50 µm, w_m = 105 µm or 22 µm) with (w_i = 9 µm) and without (w_i = 0) connecting islands. Different light intensities (4 W/cm^2 and 100 W/cm^2) were employed, assuming a 30-µs carrier lifetime.

length) semiconductor mesas, resulting in photo-induced free carriers being confined inside each mesa. Consequently, reconfigurable PI-CAI masks with much smaller pixel sizes can be generated (since "blurring" of patterns caused by lateral diffusion is eliminated) to potentially achieve THz imaging with subwavelength resolution.

To validate the proposed approach, the optical modulation properties of Si mesa-array structures were first evaluated through HFSS simulations, assuming a free carrier lifetime of 30 µs. Fig. 2(a) shows the modulation depth of mesa arrays (w_m = 105 µm, substrate thickness h = 50 µm) with fully isolated mesas (see the inset in Fig. 2(a)). It can be seen that the modulation depth only increases by ~5 dB at 625 GHz as the light intensity P_0 increases from 4 W/cm^2 to 100 W/cm^2, for mesa arrays with trench width w_t = 7 µm. Although the modulation depth can be further increased by employing smaller w_t (e.g., ~30 dB at 625 GHz with w_t = 0.5 µm), the fabrication process for such structure could be extremely challenging. An alternative solution is to add small connecting islands (indicated in the red dotted circle in Fig. 1 inset) among adjacent mesas to keep the largest gap dimensions much smaller than the wavelength. Therefore, THz wave propagation through higher order modes can be effectively suppressed, leading to a higher achievable modulation depth (under the same light intensity). Fig. 2(b) shows the modulation depth improvement by utilizing the modified mesa array designs. It can be seen that by adding the connecting islands (w_i = 9 µm), the modulation depth for modified mesa arrays with w_m = 105 µm is improved by ~13 dB at 625 GHz under a light intensity of 100 W/cm^2. A larger increase in the modulation depth can be observed for mesa arrays with smaller w_m. Assuming w_m = 22 µm, the modulation depth could be increased by ~80 dB at 625 GHz under the same light intensity (see red lines in Fig. 2(b)). This is attributed to a larger difference in the gap dimensions before and after adding the small connection islands.

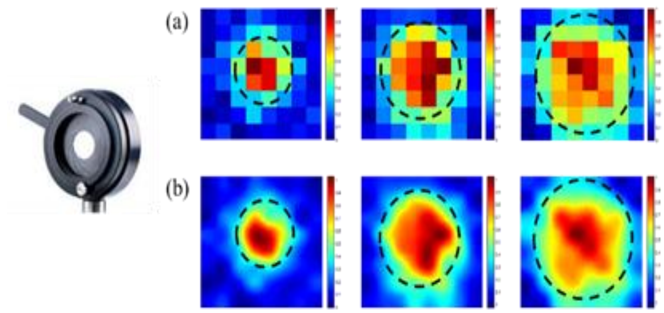

Fig. 3. THz imaging (8×8 pixels) of an iris aperture at 740 GHz using Si mesa-array structures: (a) reconstructed images of iris aperture with different sizes, (b) median filtered images for clarity. Black dashed circles highlight the dimensions of the apertures. Image size: ~12 mm × 9 mm.

III. Initial Imaging Experiments and Discussion

A Si mesa-array structure (w_m = 105 µm, w_t = 7 µm, w_i = 9 µm, h = 50 µm) was fabricated through deep reactive-ion etching (DRIE) process. An etching rate of ~5 µm/min was obtained using a combination of SF_6/C_4F_8 for etching and passivation.

The Si mesa-array structure was then tested using a WR-1.5 vector network analyzer (VNA) as the source and the detector. An optical modulation depth of ~11 dB was obtained under a light intensity of only 4 W/cm^2 in the frequency range of 740-750 GHz as expected. Once again, ~84 dB could be potentially achieved using 22-µm mesas under 100 W/cm^2 light intensity as predicted from simulation.

Initial THz imaging experiments were also performed at 740 GHz using the proposed Si mesa-array structures. On the basis of Hadamard coding, optical mask patterns can be generated through a digital mirror device (DMD) chip in a digital light processing (DLP) projector. Fig. 3 shows the reconstructed images (8×8 pixels, with an image size of ~12 mm × 9 mm) of an iris aperture with different sizes. It can be seen that the correpsonding outlines of the iris aperture (as shown by the black dashed circles) are clearly shown in the reconstructed images, indicating the validity of the PI-CAI using mesa-array structures. More advanced imaging experiments will be soon performed using more pixels (e.g., 16 × 16 pixels) with smaller pixel sizes to demonstrate THz PI-CAI with potentially subwavelength spatial resolution.

Conclusions And Future Works

A novel approach for realizing THz PI-CAI with potentially subwavelength spatial resolution is reported using micromachined mesa-array structures. The optical modulation properties of the proposed mesa arrays were first evaluated through full-wave HFSS simulations. A mesa-array structure was then fabricated and tested, and initial imaging results meet the expectations quite well. Imaging using more pixels will be soon performed to demonstrate potentially subwavelength THz spatial resolution. The proposed PI-CAI technique using mesa-array structures provides a novel approach for realizing THz imaging with subwavelength resolution.

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