Effect of the Plasmonic Enhanced Absorption and Bias Field Enhancement in Nano-Electrode THz Photo-Conductive Antennas

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***Abstract*—Metallic nano-electrodes improve the emission efficiency of THz photo-conductive antennas. But the main enhancement mechanism has not been systematically studied. In this study, we experimentally compared the effect of plasmonic enhanced absorption and bias field enhancement at the apex of nano-fingers. We concluded that the bias field enhancement dominates over the plasmon effect at low optical excitation densities. Both effects significantly saturated as the optical excitation power increases. Thus, we fabricated a large-aperture emitter for higher output power, obtained more than 1500 nA of peak-to-peak detector current with 2.5 THz of emission bandwidth.**

I. INTRODUCTION

NANO-ELECTRODES have been adopted for THz photo-conductive antennas (THz-PCAs) and photomixers (PMs) to improve the output power. Recent studies showed significant improvements [1,2], and the plasmonic enhanced absorption [1] and bias field enhancement [2] at the extremities of nano-electrodes have been pointed out as the enhancement mechanisms. In a recent theoretical paper [3], the enhancement due to the plasmonic effect is about twice times even under an optimized bias scheme. While by using a bias field singularity, the emission efficiency was enhanced by an order [4]. As many researchers are interested in high-power THz devices, clarifying the main enhancement mechanism is very important.

In this study, we fabricated and measured three different kinds of nano-structured THz PCAs, found out that under low optical excitation power densities, the bias field enhancement is much more effective than the plasmonic effect. But as the excitation power increases, the THz output power saturates, becomes less than the reference PCA's output power in some designs. For a high-power device, we fabricated nano-electrode large-aperture emitters, demonstrated more than 1500 nA of detector current with 350 mW of optical excitation at 10 V of d.c. bias.

II. RESULTS

We fabricated nano-electrode photo-conductive antennas on a semi-insulating GaAs wafer, with three different nano-structures integrated between the photo-conductive gap. The structure of each nano-electrode is shown in the inset of Fig. 1 (b). In the nano-electrode (NE) structure, the period of nano-electrode was set to be 200 nm, and the distance between the cathode and anode was 3 μm. In the nano-gap (NG) structure, the distance was reduced to 200 nm. In the shifted nano-gap (SNG) structure, the fingers were alternately shifted in the parallel direction to form an inter-digit region of 1 μm width. A reference PCA was also fabricated for comparison.

The fabricated nano-PCAs were measured by a standard time-domain spectroscopy setup. The relative power enhancement of nano-PCAs compared to the reference are shown as a function of the power and the polarization of the optical excitation, as shown in Fig. 1 (a) and (b). We found out that the polarization dependence was only found in SNG structure, while the NE structure is more efficient than the NG structure. This implies that the plasmonic enhancement is effective for the SNG structure which efficiently collects the plasmonic carriers for the perpendicularly polarized excitation, and the carriers generated between the cathode and the anode of the NE structure is much more effective than the plasmonic carriers of the NG structure.

The most important observation is both effects saturate as the optical power increases. The reason for the saturation is due to the field-enhanced carrier collection through the apex of the nano-fingers. Due to the point-like nature of the apex, the NG and NE structures are prone to the bias-field screening effect due to the high-density local carriers in the vicinity of the apex. In contrast, in the SNG structure, the field is collected via the inter-digit region where the carrier collection is enhanced due to the bias field. The increased carrier collection area reduces the saturation effect under higher optical excitation power, compared to the NG and NE structure. Note also that the field-enhanced plasmonic carrier collection in the SNG structure also manifests the plasmonic effect, as can be seen by the polarization-dependent THz emission efficiency.

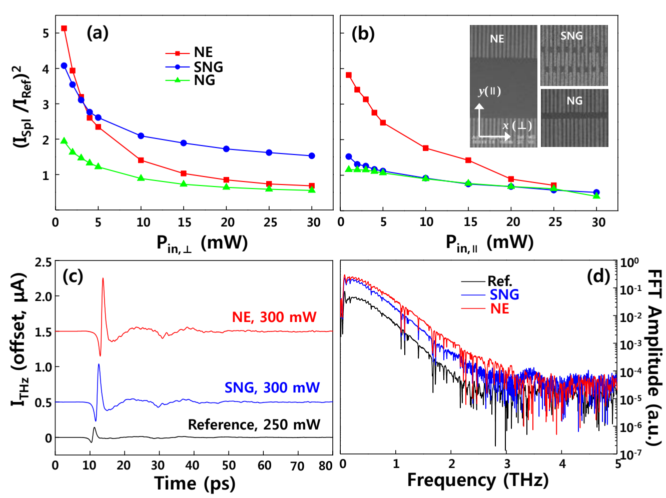

Fig. 1. Power enhancement of nano-electrode PCAs relative to a reference PCA as a function of optical excitation power polarized in (a) perpendicular and (b) parallel polarization. (c) Time-domain curves of THz pulse emitted from nano-electrode large-aperture emitters. (d) FFT spectrum of curves in (c).

At low optical excitation power, the nano-electrode structures are more efficient than the reference PCA. This is attributed to the reduced bias-field screening effect. Thus, we fabricated large-aperture emitters for the maximum efficiency, achieved 1500 nA of peak-to-peak current in the THz time traces. This corresponds to more than 200 μW of average power, measured by a commercial pyroelectric detector (THz-5I-BL-BNC, Gentec-EO). Up the 350 mW of optical excitation, the maximum power available to us, we observed no saturation. Even after transmitting through a 1.5 mm of liquid water, the peak-to-peak current was more than 6 nA, enough for THz imaging. In addition, the technology is scalable, which promises much more THz power by an increased aperture size and optical excitation power. The enormously increased THz power may find applications in the medical in-depth imaging [5], the THz near-field microscopy [6] and any kind of THz applications demanding high-power pulse emitters.

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