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Plasmonic terahertz antennas with high-aspect ratio metal gratings

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The state-of-art terahertz (THz) emitters and detectors are of great interest due to its wide applications in security systems, biology, medicine and material science [1–3]. Despite the variability of existing THz generation principles photoconductive antenna (PCA) is still promising THz emitter for broadband THz spectroscopy and imaging. Since its first demonstration by Auston's research on silicon substrate [4], numerous studies have been carried out. Despite the considerable progress in developing PCAs there are still challenges such as increasing an emitted THz power, an optical-to-THz conversion efficiency, a bandwidth of a PCA and its thermal stability.

In present article, we present a novel technology with a passivation approach for fabricating a dielectric-filled plasmonic PCA that allows us for reaching a 100 nm-height plasmonic gratings and strongly reduce leakage currents. In the proposed technology two different dielectrics are separately used: a Si_3N_4 for preliminary passivating a surface of a photoconductor to reduce a dark current flow and Al_2O_3 dielectric for filling and covering plasmonic gratings to increase an incident light coupling. This approach allows for sustaining a thermal stability of a PCA and is suitable for any photoconductive material, due to excluding a mesa etching, which is of particular importance for InGaAs-based PCAs.

It is well known that all types of PCAs, especially the log-periodic and log-spiral antennas, suffer from high leakage currents, because a dark current flows between the full length of the antenna bias lines which is hundred times longer than the optical excitation spot. In order to significantly decrease a dark current flow we have developed a novel technology for a PCA fabrication where an antenna metallization, including contact pads, is deposited on a photoconductor's surface preliminary covered (i.e. passivated) with a dielectric through etched windows. The schematic layout of the proposed PCA is depicted in Fig. 1.

Prior to fabrication process we carried out numerical calculations by means of a 2D finite element method-based solver for analyzing the interaction between a TM-polarized laser pump beam and plasmonic gratings. The calculation domain consisted of 4 periods of plasmonic gratings (4×200 nm) with width and distance between them equal to 100 nm, deposited on 3-µm GaAs substrate. First, we calculated an electric field near plasmonic gratings distribution versus a height (h) of metal gratings which showed that an increase of metal height leads to a continuous enhancement of an electric field and its maximum is shifted toward high values of h, which is difficult to being experimentally achieved according to chosen high aspect-ratio of gratings, which is defined as the ratio between a width of a grating to its period.

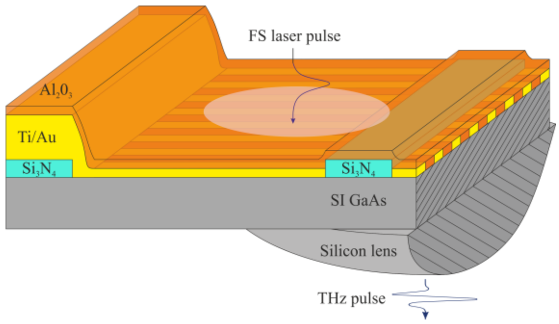

Fig. 1. Schematic layout and operation principle of the proposed dielectric-filled plasmonic THz emitter with high-aspect ratio metal gratings. A lower dielectric Si_3N_4 layer is used for reducing leakage currents (to sustain a thermal stability enhancement) while an upper Al_2O_3 dielectric serves for filling a distance between gratings and covering them to increase an incident light confinement. Also it acts as an anti-reflection coating layer

Thus we considered the case of h = 100 nm with aspect-ratio equal to 0.5, that to our knowledge has not been reached experimentally yet. Second, we estimated an optimum thickness of Al_2O_3 dielectric layer which entirely fills a distance between gratings to enhance a light coupling and simultaneously mitigate the Fresnel reflection losses for the case of h = 100 nm. We demonstrated that the dependency of an incident laser pump reflection coefficient on Al_2O_3 thickness (d) has a minimum which corresponds to 180 nm thickness of Al_2O_3. Afterwards, when fabricating the PCA, we used these parameters of the dielectric thickness and plasmonic gratings height, i.e. d = 180 nm and h = 100 nm, respectively.

Figure 2 shows scanning electron microscope (SEM) image of the fabricated dielectric-filled plasmonic PCA with log-spiral topology and a magnified image of plasmonic gratings. Initially we passivated GaAs photoconductor's surface by 230 nm Si_3N_4 dielectric, where the windows for 50/450 nm Ti/Au antenna electrodes were etched. Therefore antenna electrodes were deposited on a photoconductor's surface only through the etched windows in Si_3N_4 while a PCA's gap remained passivated. Plasmonic gratings were formed by electron-beam lithography with 18/75 nm Ti/Au metallization followed by lift-off. The PCA fabrication is partially described in Refs. [5,6].

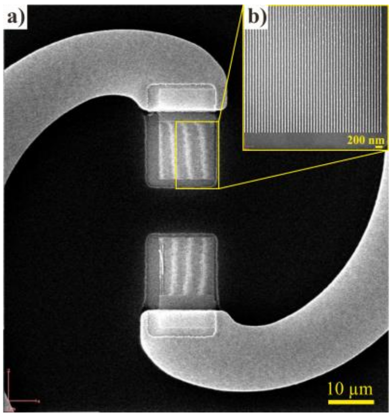

Fig. 2. SEM image of the fabricated plasmonic PCA (a) with a magnified image of plasmonic gratings (b)

The experimentally-measured current-voltage characteristics without laser illumination (see Fig. 3) demonstrated significant reduction of a dark current when a surface of GaAs is passivated by Si_3N_4 in comparison to a non-passivated one (more than three orders of a magnitude) demonstrating that the selected size of window in Si_3N_4 leads to strong decrease of a dark current, keeping a transient photocurrent remained.

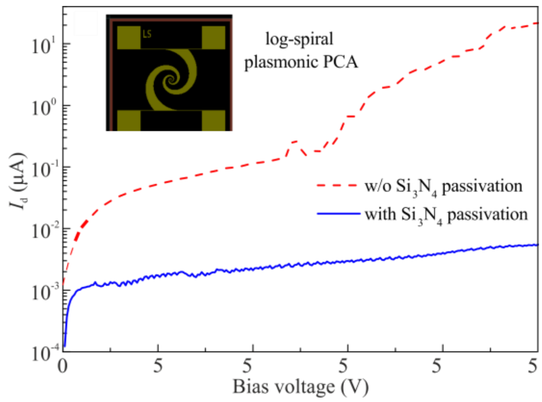

Fig. 3. Current-voltage characteristics without laser illumination measured for the proposed PCA when using Si_3N_4 dielectric (solid line) and without it (dashed line)

In order to demonstrate a performance of the proposed PCA we examined it by means of THz time-domain spectroscopy and compared to the traditional one. The both PCAs were used as a THz emitter, while compact all-fiber-based Toptica FemtoFErb780 laser was used as pump source with mean power up to 10 mW with a bias voltage equal to 30 V. As seen in Fig. 4 the spectra shape remain unchanged for the both PCAs, but the proposed PCA demonstrates 2000-100 times increase of the emitted THz power depending on laser pump (not attached in this article). Since PCAs are saturated at high laser pump due to electric field screening, we additionally investigated the emitted THz power versus laser pump in order to find out an optimum illumination regime. We showed that the transient photocurrent for the proposed and traditional PCAs is trending to converge at laser pump close 10 mW, though at low pump energies the transient photocurrent generated by the proposed PCA is up to 25 times higher than for the traditional one.

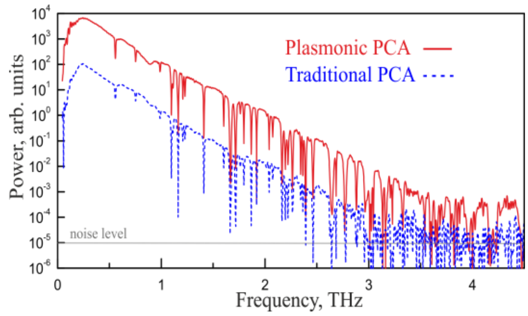

Fig. 4. Radiated THz power in the frequency-domain for the plasmonic and traditional PCAs based on SI-GaAs photoconductor

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