Efficient 3-dimensional photonic-plasmonic photo-conductive switches

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Abstract—The efficiency of Terahertz photo-conductive switches was overlooked for a very long time. These optoelectronic devices have been dominating so far the fields of optics and ultrafast spectroscopy, however nowadays they are making their way through to new and emerging fields of research where power efficiency is of great importance. To address the efficiency problems, in this contribution, we present a new photo-conductive switch whose design is 3-dimensional. In contrast to conventional planar designs, the proposed photo-conductive switch can enhance the overall efficiency by increasing the optical absorption within the device, while at the same time maximizing the carrier collection, which in turn leads to better performance. The design of this novel photo-conductive switch takes advantage of photonic and plasmonic modes that are excited in the device due to a periodic array of nanopillars, whereas the collection efficiency is optimized by converting each nanopillar into a single nano-photo-conductive switch. By numerically simulating this novel device, we show a 50-fold increase in the overall generated current and a 5-fold bandwidth increase compared to traditional interdigitated planar photo-conductive switches. The first prototypes of this novel device are fabricated and preliminary measurements are ongoing. This opens up a wealth of new possibilities in research fields where efficient low power devices are indispensable.

I. INTRODUCTION

The efficiency of THz photo-conductive switches has been steadily improving over the last few years. Several studies have shown that their efficiency can be improved by increasing the optical absorption within the semiconductor. This was achieved by incorporating plasmonic electrodes on the semiconductor surface that can resonantly increase the laser absorption or by other photonic designs that can trap optical modes within the semiconductor [1-3]. Although, all of these studies have successfully addressed the optical absorption within the semiconductor not many works have dealt with the collection efficiency of the generated carriers by the electrodes. An ideal device should maximize the optical absorption as well as the collection of the photo-generated carriers.

II. RESULTS

In this work we propose a novel photo-conductive switch that maximizes the absorption efficiency of the laser light, while at the same time it increases the collection efficiency of free carriers. As shown in Fig. 1, the proposed photo-conductive switch device is a periodic array of several hundreds of vertical 3-dimensional nanopillars made from LTG-GaAs. The array of GaAs nanopillars is embedded in a transparent polymer layer. The top of each pillar is covered by a silver cap that ensures an electrical contact. At the bottom of the pillars, a continuous silver layer (surrounding the base of the pillars) play the role of the bottom electrode. Finally, all the top contacts are connected using a layer of transparent metal (i.e. ITO).

The optical absorption within this structure is maximized by photonic and plasmonic modes supported by this array. The dimensions and periodicity of the proposed photo-conductive switch were optimized such that the photonic modes supported by this structure dominate over the plasmonic modes. This is because in plasmonic-based devices, a significant fraction of the optical power is absorbed by the metal and converted into heat. Basically, the design rules of our devices were based on an optimization of the device geometry that will allow the simultaneous excitation of three kind of electromagnetic resonances [6].

First for ease of practical use, we have considered that the device is illuminated under normal incidence by a laser beam with a 780 nm central wavelength. The first photonic mode is a direct result of the device’s periodicity. The periodic array of pillars plays the role of a 2D grating coupler that allows the excitation of a guided mode in the x-y plane; that is the area defined between the ITO and the bottom Ag electrodes. The combination of polymer and LTG-GaAs pillar array constitutes an effective medium that can support the excitation of a TE0 guided mode. The propagating TE0 mode then couples to a second photonic mode within the LTG-GaAs nano-pillars. This mode is a 2nd order Fabry-Perot (FP) resonance excited in the vertical direction defining the height of the nano-pillars (z direction). The FP mode is ‘dark’ in nature and cannot be excited by a normal incidence wave due to the Ag cap on the top of each nano-pillar. The third optical mode supported by the proposed device is a surface plasmon polariton (SPP) mode propagating on the bottom Ag metal electrode. This mode is weakly excited to reduce losses due to heat conversion.

We first define the geometrical parameters of our device starting from analytical solutions of the Fabry-Perot, and waveguide problems. The approximate dimensions of the pillar array are periodicity: 355 nm, height: 330 nm, width: 140 nm. The geometry was numerically optimized using the Wave Optics module of Comsol Multiphysics. Our numerical simulations, summarized in Fig. 2, show that due to the
excitation of photonic/plasmonic modes in our device we can achieve an absorption efficiency higher than 95% (red line), out of which 80% is absorbed by the semiconductor (black dashed line) whereas the remaining is converted into heat due to the plasmonic modes (grey dashed line).

To increase the collection efficiency of the free carriers we positioned the two bias electrodes on the top and bottom of the nanopillar. As a result, each and every one of the nanopillars operate electrically as individual photo-conductive switches. One of the novelties of the proposed design is that the top electrode is a transparent metal (i.e. ITO), whose thickness can promote anti-reflection properties. Positioning the electrodes on the top and bottom of the nanopillar has the advantage of creating a homogeneous electric potential along the pillar height that can uniformly accelerate the free carriers [3]. Due to the short distance between the two electrodes, the electric potentials can reach values greater than 100 kV/cm. This is in stark contrast to conventional planar photo-conductive switch designs, where the electric potential is not homogeneous but it strongly depends on the geometry of the electrodes as well as their physical separation.

Because of the very high values of the DC electric field that will accelerate the photogenerated carriers in the GaAs pillars, we had to consider possible velocity overshoot for the free carriers in order to provide the correct mobility model to the semiconductor equations since our nano-pillar device has sub-micrometer dimensions. Furthermore, the velocity is not only electric field dependent but is additionally time-dependent, which means that the carriers’ drift velocity will change as a function of time and bias electric field. By performing Monte-Carlo simulations on a system where the only input parameters were the GaAs band structure, carrier density and bias electric field, we captured the drift velocity (mobility) of the free carriers as a function of time and electric field [4]. The results from our Monte-Carlo simulations were used as an input parameter for solving the nano-pillar semiconductor equations using the Semiconductor module of the commercial software Comsol Multiphysics. The LTG-GaAs media was considered to have the same electrical properties as GaAs except for a shorter carrier lifetime (0.8 ps). As compared to GaAs nano-wires where very high surface recombination velocity can be observed [5], we have considered that the size of the nano pillars is sufficiently large such that the carrier dynamics will be dominated by the bulk recombination or trapping of the photogenerated carriers.

Our numerical calculations (Fig. 3) show that the nanopillar photo-conductive switch excited by a 100 fs laser pulse has a 50-fold increase in the overall generated current and a 5-fold bandwidth increase compared to traditional interdigitated planar photo-conductive switches [6]. In order to take into account the impact of the capacitance of the device onto its response, we have calculated the equivalent capacitance of a single nano-pillar unit cell to be 15 aF. For a device of 9 x 9 μm²; this leads to a capacitance of 0.01 pF. Consequently, the circuit bandwidth is limited by a 1 ps RC response time for a 100 Ω load. The photocurrent burst generated by this device is shown in the inset of Fig. 3. As compared to a classical planar device, the peak current is still one order of magnitude larger.

We are currently working towards a prototype of this photo-conductive switch to confirm its improved efficiency. The scanning electron microscope image of Fig. 1 corresponds to the first fabricated device and optical and electrical characterizations of this device are currently ongoing.

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