Microlens coupled interdigital photoconductive switch

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A large-area terahertz emitter based on an interdigital finger electrode photoconductive switch on low-temperature grown GaAs attached to a hexagonal microlens array is demonstrated. The hexagonal arranged microlenses direct the incident IR excitation pulses into specified electrode gaps, resulting in constructive interference in the terahertz far field. Using a Ti:sapphire oscillator running at 80 MHz with 150 fs pulses, 6.5 μm THz average power at 540 mW optical excitation is obtained. The maximum IR-to-terahertz conversion efficiency achieved is $\geqslant 1.35\times 10^{-5}$. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2976162]

During the past two decades, the investigation of coherent sources for the terahertz region of the electromagnetic spectrum ($10^{11}-10^{13}$ Hz) has attracted growing interest in many fields of science and technology. Ultrashort terahertz pulses have become an important technique for time-resolved spectroscopy, nondestructive materials testing, medical imaging, and homeland security applications. Over the years, different concepts have been developed to increase the available terahertz power and bandwidth.[1–4] However, the original setup based on photoconductive (PC) emitters and antennas still provides the highest dynamic range for measurements around 1 THz.[5] The recent progress in ultrafast laser sources motivates research on improved antenna concepts, which can benefit from high power laser systems under avoidance of optical breakdown or saturation effects.

The very first PC switches had active areas of about a few μm^2 yielding breakdown thresholds around 10–20 mW optical excitation. Several attempts have been investigated to achieve an improved IR power utilization. For instance, one can simply enlarge the electrode spacing. While this decreases the excitation density on the emitter, high pulsed voltage fields in the kilovolt regime must be applied in order to achieve a sufficient electric field strength within the electrode gaps. Consequently, electromagnetic leakage fields occur that interfere with sensitive electronics inside the laboratory.[6]

Dreyhaupt *et al.* presented an innovative terahertz emitter concept based on an interdigital electrode metal-semiconductor-metal structure processed on semi-insulating GaAs (SI GaAs). They masked every second electrode gap by an additional metalization layer in order to achieve photo-induced charge carrier acceleration only in those electrode gaps that exhibit an unidirectional electric field.[7] As a consequence, only constructive interference appears in the terahertz far field. Nevertheless, due to the process-related metal coverage around 75% and the reflectivity of the semiconductor surface, only approximately 20% of the incident pump power can contribute to the generation of terahertz radiation. In 2007, Awad *et al.* demonstrated an alternative fabrication concept for an interdigital finger electrode emitter based on substrate transferred thin films of low-temperature grown GaAs (LT GaAs).[8] On the one hand, this epitaxial lift-off technique allows versatility in the choice of substrate materials and furthermore reduces the influence of dark current by at least 50% due to the complete elimination of LT GaAs within inactive electrode gaps. However, on the other hand, an epitaxial lift-off complicates considerably the fabrication process yielding higher manufacturing times and costs. Moreover, in comparison with the emitter presented by Dreyhaupt *et al.* no remarkable improvement in the case of pump power utilization is achieved.

Here we present a different approach for an interdigital finger electrode emitter. It is based on the application of an hexagonal microlens array which is coupled to the emitter structure. The lenses are attached in such a way that only every second gap is illuminated by the incident IR beam. As a consequence, here, a unidirectional excitation of the generated charge carriers under the avoidance of any additional shadowing layers or epitaxial lift-off is achieved. Furthermore, approximately three-fourths of the applied IR light can contribute to the generation of terahertz radiation. This is an at least three times higher laser utilization in comparison to the large-area emitters demonstrated by Dreyhaupt and Awad, respectively.[7,8]

In the following, this emitter structure will be explicitly described. We processed two interdigital Ti/Pt/Au finger electrodes by optical lithography on the surface of a 3 μm LT GaAs layer grown on a 650 μm thick SI GaAs substrate. LT GaAs has subpicosecond carrier lifetime and can therefore be used interchangeable as terahertz emitter or detector. The electrode widths were conceived as 8 μm whereas the electrode spacing was 5 μm. The whole dimension of the electrode structure was 300×300 μm^2. In addition, a dielectric antireflection coating consisting of a 63.9 nm thick Ta_2O_5 layer upon 27.3 nm SiO_2 was added. For a lens diameter of 27 μm, a lens pitch of 30 μm, and a hexagonal packaging, an overall density of 73.4% is achieved. A photo of the emitter structure without and with coupled microlens array can be seen in Fig. 1.

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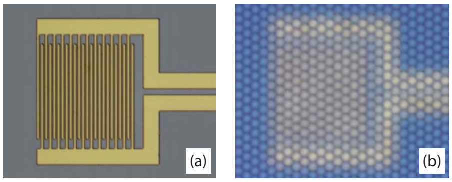

FIG. 1. (Color online) Photo of the large-area emitter without (a) and with hexagonal lens array (b).

In our experiments, we used a conventional Ti:sapphire laser driven terahertz time-domain system (TDS) schematically shown in Fig. 2. The laser oscillator delivered 150 fs pulses at 800 μm at a repetition rate of about 80 MHz. The maximum applied IR power was 540 mW at a laser spot diameter of about 150 μm $(1/e^2)$. The electrodes were biased with a 30 kHz, 25 mV square wave voltage. The generated terahertz trains emitted through a hyperhemispherical silicon lens on the emitter's backside were collimated and refocused with the help of two off-axis parabolic mirrors. For coherent detection, we used a LT GaAs antenna with a photoconductive gap of 6 μm. The induced signal was amplified and recorded using a lock-in amplifier. In addition, we measured the average terahertz power using a pyroelectric detector on the basis of a $LiTaO_3$ crystal with an active element size of 6 μm^2. The experimental data are plotted in Figs. 3 and 4, respectively. For a maximum incident pump power of $P_{opt}=540$ mW and an applied electric field strength of $E_{bias}=5$ MV/m, approximately 6.5 μW THz average power is achieved.

For the generation of terahertz radiation due to the formation of photoinduced electric dipoles, the emitted terahertz field is proportional to the charge carrier density ρ_{opt} and the local electric field E and can therefore be expressed by

$$E_{THz} \propto \rho_{opt} \cdot E \propto \frac{P_{opt}}{A} \cdot E, \quad (1)$$

where P_{opt} is the IR average power incident on the area A. As a consequence, the emitted terahertz power P_{THz} is determined by

$$P_{THz} \propto \left(\frac{P_{opt}}{A} \cdot E\right)^2. \quad (2)$$

Hence, the terahertz power increases quadratically with the electric field strength and the optical power. However, this parabolic dependency can only be valid for the absence of any saturation effects. Basically, such effects have two different origins. First, for high optical fluences, the space-charge field generated by the free carriers becomes comparable to the applied bias field and a screening occurs that

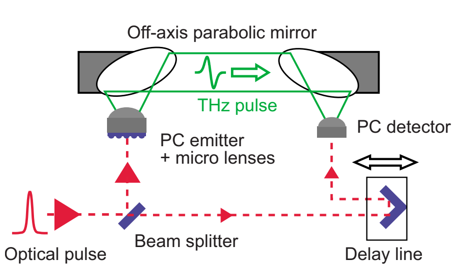

FIG. 2. (Color online) Schematic of the terahertz TDS.

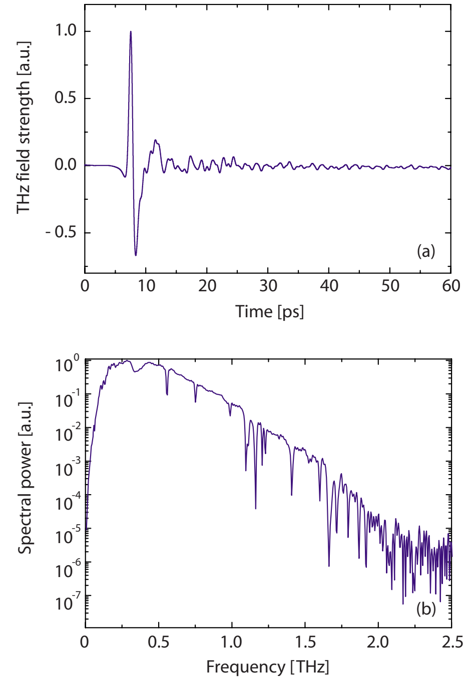

FIG. 3. (Color online) Time-domain terahertz field scan for an acceleration field of 5 MV/m (a), corresponding spectral power (b).

yields a deceleration of the electrons.[9,10] Moreover, the acceleration itself is limited by the saturation velocities of the electrons due to the increasing probability for intervalley scattering.[11] In the case of the cubic III-V semiconductors

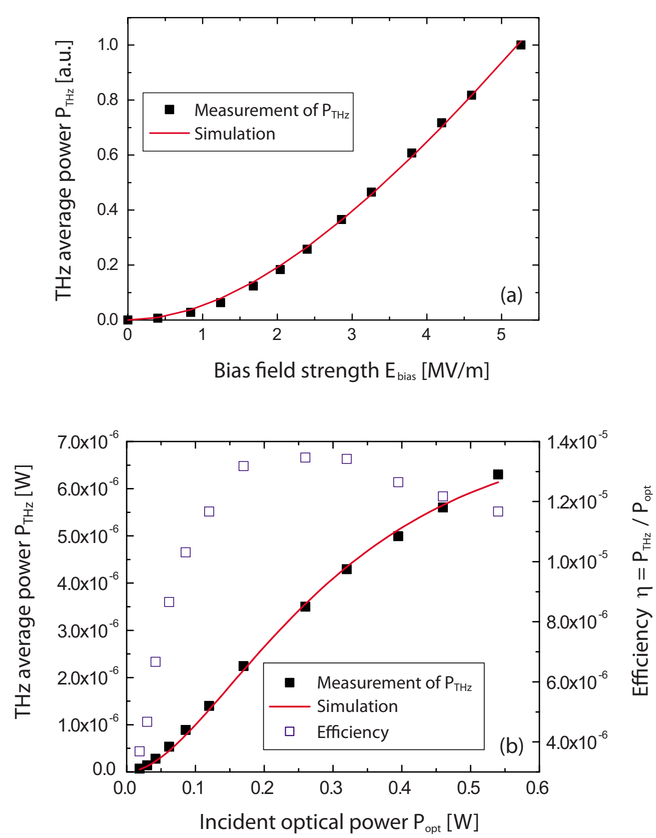

FIG. 4. (Color online) Terahertz average power dependency for (a) increasing bias field strength and (b) increasing incident optical power with $E_{bias}=5$ V/m. Maximum achieved net conversion efficiency $\eta = P_{THz}/P_{opt} \approx 1.35 \times 10^{-5}$.

such as GaAs the carriers in the L or X valleys have higher effective mass and therefore cannot contribute to the terahertz emission. Taking this into account, Eq. (2) has to be modified:

$$P_{\mathrm{THz}} = \frac{CE_{\mathrm{bias}}}{A^2} \cdot E_{\mathrm{sat}}(1 - e^{-E_{\mathrm{bias}}/E_{\mathrm{sat}}}) \cdot P_{\mathrm{sat}}^2(1 - e^{-P_{\mathrm{opt}}/P_{\mathrm{sat}}})^2, \tag{3}$$

where E_{sat} and P_{sat} are the saturation electric field strength and saturation optical power, respectively. C is an emitter specific constant that represents all conversion efficiency parameters determined by the material itself and the electrode design. It includes, among other properties, the recombination lifetime, relaxation, and trapping time of the accelerated charge carriers as well as an estimated outcoupling efficiency of about 0.7 due to the high refractive index of the semiconductor ($n_{\mathrm{THz}} \approx 3.5$). Additionally, only one direction of the generated terahertz radiation can be collected for further applications which has to be considered as an additional factor 1/2. The saturation electric field strength can be easily obtained by measuring the terahertz average power as a function of the applied electric field strength [see Fig. 4(a)]. It can be seen that the quadratic dependency is nearly preserved which agrees well with an estimated $E_{\mathrm{sat}} \approx 5.2$ MV/m. In the second step, we obtained the specific constant $C \approx 3 \times 10^{33}$ m^4/V^2 W^2 and $P_{\mathrm{sat}} \approx 0.22$ W by investigating the dependency between the generated terahertz average power and optical excitation for an applied bias field strength of $E_{\mathrm{bias}} = 5$ MV/m. The results are given in Fig. 4(b). As one can see, Eq. (3) reproduces very well the experimental observations. The highest conversion efficiency $\eta = P_{\mathrm{THz}}/P_{\mathrm{opt}} \approx 1.3 \times 10^{-5}$ is obtained for an optical excitation in the range of 200–300 mW. Due to the saturation effects, the emitter area should be enlarged for higher pumping levels in order to ensure optimum conversion efficiencies. Scaling up the emitter size comes along with two further significant consequences. On the one hand, an increased emitter structure radiates in a smaller cone which improves the amount of collected terahertz radiation.[8] On the other hand, as soon as the radiation area becomes larger than the generated terahertz central wavelength, one cannot longer assume a point-shaped radiation source. In order to avoid aberration, an adaption of the applied terahertz optical elements should be realized.

In conclusion, we demonstrated a large-area terahertz emitter device on the basis of a hexagonal microlens array which was attached to an interdigital finger electrode structure. The application of a microlens array is a convenient technique to control the illuminated emitter areas for an improved IR-to-terahertz conversion. In comparison to former finger electrode emitters, here, no shadowing layers or additional etching processes are needed. This considerably simplifies the fabrication process and also improves pump light usage. In addition, this approach paves the way for future microlens applications in the face of local resolved terahertz radiation, cameras, or beam shaping elements based on PC switches.

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