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Large-area laser-driven terahertz emitters

G. Klatt, D. Stephan, M. Beck, J. Demsar and T. Dekorsy

Intense terahertz emitters are one of the most important components of terahertz (THz) time-domain spectroscopy systems. In this presented report, the development of THz emitters over the last two decades is reviewed, and an outlook for future THz emitters is given. The physical principle behind the THz generation process is discussed for two types of emitters: state-of-the-art large-area photoconductive emitters are compared to THz emitters based on the photo-Dember effect. The latter do not require an external bias voltage. This passive character of the photo-Dember emitters has several advantages which are outlined.

The first photoconductive switch with electromagnetic waves in the picosecond regime was shown by Auston in 1984 [1]. The frequent employment of these 'Auston switches' then became established with the wide availability of femtosecond lasers such as the Kerr-lens mode-locked titanium:sapphire in the 1990s. The most commonly used THz sources were subsequently based on either photoconductive switches [2] or the emission from semiconductor surfaces [3], in both cases irradiated with femtosecond laser beams. To date, these two methods introduced 20 years ago are still commonly employed for generating, by optical excitation, THz radiation in the frequency range 0.2–5 THz [4, 5]. Advances have also been made in the generation of THz radiation via optical rectification or difference frequency mixing [6, 7], but these will not be discussed further in this Letter.

Typically, the peak frequency of photoconductive sources or bare semiconductor surfaces lies around 1 THz, and the spectral coverage is limited to 3 THz. Drawbacks of these sources are the lack of long-term stability, scalability and the low conversion efficiencies from the optical to the THz regime. Further research led to the development of large-area photoconductive emitters [8–10], which exhibit one order of magnitude larger conversion efficiency compared to the first sources. Furthermore, recently it has been shown that, with an improved excitation geometry, conversion efficiencies up to 2×10^{-3} are possible [11]. A new concept for the generation of intense THz radiation is based on the lateral photo-Dember effect [12]. Inspired by the large-area photoconductive emitters, these new emitters allow scalability, but do not require an external bias voltage.

The common feature of these THz generation methods is the emission of electromagnetic radiation from accelerated carriers in semiconductors such as gallium arsenide (GaAs) or indium gallium arsenide (InGaAs) [13]. Free carriers – electrons and holes – are generated at the surface of the semiconductor by femtosecond pulses with a photon energy above the gap energy of the semiconductor. For conventional photoconductive switches, electrodes deposited on the substrate material are externally biased and hence an electric field exists between the electrodes. The accelerating electric field E_{ext} is given by the externally applied voltage U_{ext} divided by the electrode spacing d. After photoexcitation, a time-dependent dipole oriented parallel to the surface builds up when the photogenerated electrons and holes are accelerated and separated in the electric field (see Fig. 1*a*). Owing to the higher mobility of the electrons compared to the holes, the electrons are mainly accelerated and contribute to the THz emission [14]. Owing to the dipole orientation, the generated THz radiation is then principally emitted in the forward and backward directions under normal incidence (see Fig. 1*a*).

A less common way to generate THz radiation is the photo-Dember effect [14, 15]. This effect arises when electron-hole pairs are generated with a strong spatial gradient. In the simplest case, this occurs after optical excitation of a highly absorbing semiconductor surface which results in a carrier gradient perpendicular to the surface. Owing to different diffusion constants of electrons and holes, a space charge field E_{Dember} between the diffusing carrier distributions builds up. The photo-Dember field couples the diffusion of electrons and holes, and leads to ambipolar diffusion. Under pulsed excitation, this happens a short time after the initial generation process, and depends on the carrier gradient and the carrier densities [16, 17]. In the steady-state case, the photo-Dember field E_{Dember} can be estimated, under certain assumptions, from the drift-diffusion equation for electron and holes in combination with the Einstein relation [18]:

$$E_{Dember} = \frac{k_B T}{e}\left(\frac{1}{n}\right)\left(\frac{\mu_e - \mu_n}{\mu_e + \mu_n}\right)\frac{dn}{dx}$$

where μ_e and μ_h are the mobilities of electrons and holes, respectively. n is the carrier density (the optically excited electron density is assumed to be equal to the hole density) and x the spatial co-ordinate perpendicular to the surface. Experimentally the generation of THz radiation based on the photo-Dember effect has been observed for many different strongly absorbing semiconductors [17, 19–26]. The time-dependent dipole connected with the THz emission is oriented parallel to the optically excited carrier gradient and hence perpendicular to the excited surface. This is one of the drawbacks of THz generation by the photo-Dember effect – as well as for THz generation by surface field screening [27] – because for optimal excitation conditions at an angle of incidence of 45°, the out-coupled THz radiation is a factor of two smaller than for a dipole oriented parallel to the surface. Another limitation is the strength of the initial carrier gradient, which is given by the intrinsic absorption coefficient of the semiconductor at the excitation wavelength.

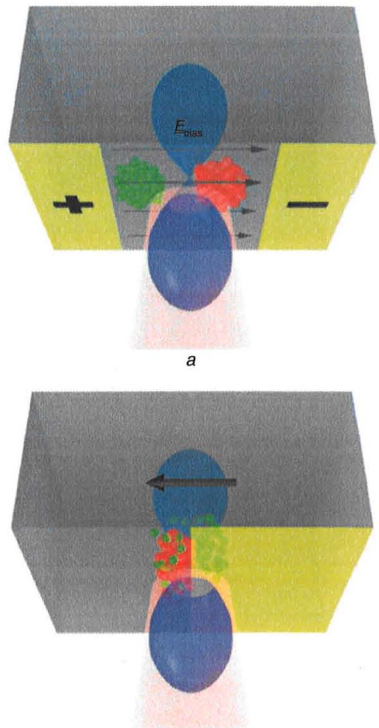

Fig. 1 *Principle of THz emission from (Fig. 1a) a photoconductive switch and (Fig. 1b) lateral photo-Dember currents*

In the case of a photoconductive switch, an external applied bias generates an electric field E_{bias} between the two electrodes. A femtosecond laser pulse (red cone) creates photoexcited carriers in the semiconductor grey. The electrons (green spheres) are accelerated towards the positive electrode, the holes (red spheres) towards the negative electrode. In contrast to the photoconductive switch, the photo-Dember emitters do not require external biasing. Here, photoexcitation of a partially metalised semiconductor surface with a femtosecond laser pulse results in a strong gradient in the carrier density at the edge of a metalised stripe. Since the photoinduced electrons diffuse much faster than the holes this gives rise to a photo-Dember field E_{Dember} perpendicular to the edge of the metalised stripe. In both pictures the blue lobes indicate the dipole radiation patterns of the arising THz radiation

To overcome these limitations the idea of lateral photo-Dember currents was suggested. In this case, the carrier gradient and therefore the time-dependent dipole is rotated by 90°, so that they are oriented parallel to the excited surface. This rotation can be easily achieved by partially shadowing the excitation area (see Fig. 1*b*). The strength of this gradient can be significantly higher than that obtained through the intrinsic absorption length of a semiconductor [12]. A proof of this simple design is given in Fig. 2*a*. The peak-to-peak amplitude of the emitted THz electric field is taken from a series of transients acquired at different positions relative to a metal edge underneath the laser spot. For details of the experimental setup we refer to [12, 28]. Fig. 2*b* shows the time transients when the laser spot is located at the metal-semiconductor edge. Depending on the edge (left or right) the time-domain data reveal a flipped single cycle electromagnetic emission indicating the change of the emitted THz electric field. Owing to the much higher electron

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mobility, the electrons diffuse faster underneath the metallic stripe than the holes, leading to the sign flip from the left to the right edge.

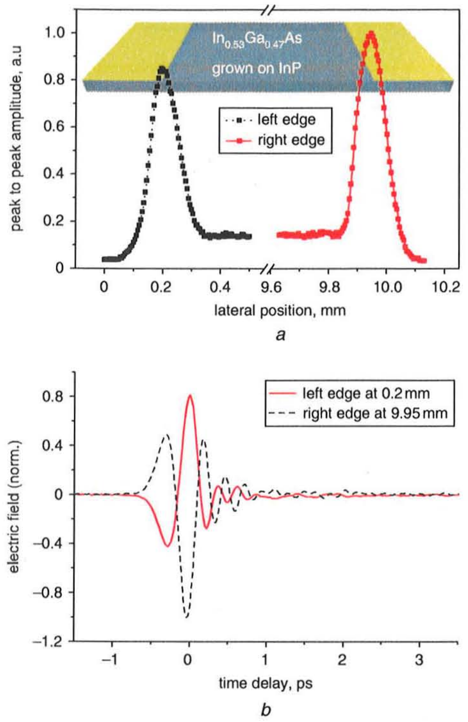

Fig. 2 *Peak-to-peak amplitude of emitted THz electric field when metal-semiconductor edge shown in background is moved underneath the laser spot. The line scans are normalised to the peak-to-peak amplitude at 9.95 mm. (Fig. 2b) Fig. 2b shows THz transients emitted from left and right metal-semiconductor edge when Gaussian-shaped optical excitation spot located exactly on metal edge. Left and right correspond to (Fig. 2a). The transients normalised to maximum electric field value at right edge*

The orientation of the time-dependent dipole generating the THz radiation is an important factor for multiplexing the THz generation process and hence scaling up the active area. If the dipole is oriented parallel – as in the case of the photoconductive switch and the lateral photo-Dember currents – multiplexing can be achieved by periodically adding emitter elements laterally (see Figs. 3*a* and *b*). This is achieved by creating a metal-semiconductor-metal (MSM) structure processed by optical or electron beam lithography. For the photoconductive emitters, the electrode widths and spacings are chosen to be 5 μm. To avoid destructive interference of the THz radiation in the far field, it is important that every second gap between two electrodes – where the field is pointing in the opposite direction – is covered with an additional metallisation isolated from the electrodes [8]. This guarantees a coherent superposition of the THz radiation in the far field owing to unidirectional acceleration of the carriers over the entire active area (see Fig. 3*a*). The problem of high-voltages necessary for intense THz emission by single photoconductive switches is solved by keeping the gap dimensions small. In that case typical values for the acceleration field of the order of several tens of kilovolts per centimetre are easily obtained with low voltages. With these large-area photoconductive emitters of $10 \times 10\ \text{mm}^2$ dimensions we demonstrated the generation of a peak electric field of the THz pulse in vacuum of 36 kV/cm when exciting the emitter with a pulse energy of 2.7 μJ [11].

An analogous concept for the multiplexing of photoconductive switches is also used for the photo-Dember emitters. The excitation of several periodic metal stripes would lead to destructive interference of the THz radiation in the far field, since the two carrier gradients of every stripe point in opposite directions. To achieve unidirectional carrier gradients and hence constructive interference in the far field, every second carrier gradient must be suppressed. Fig. 3*b* shows one possibility to realise unidirectional carrier gradients experimentally, i.e. through wedged metal stripes. They generate strong carrier gradients at their thick opaque edge, while weak carrier gradients are obtained at the opposite side where the edges becoming thinner and transparent. The Dember emitters discussed here are fabricated with a stripe width of about 2 μm and a spacing of 1 μm and have a size of $1 \times 1\ \text{mm}^2$. At the moment the size is limited by the fabrication process.

A comparison of the multiplexed emitters was performed in a rapid-scanning THz precision spectrometer based on asynchronous optical sampling, as shown in Fig. 4 [28, 29]. At a repetition rate of the femtosecond laser of 1 GHz the pulse energies are small (less than 1 nJ), so that the excitation spot can be set to 55 μm full-width-half-maximum without running into saturation effects. The photo-Dember emitter is manufactured on the same $In_{0.53}Ga_{0.47}As$ substrate as the single metal-semiconductor edge shown in Fig. 2*a* and shows a four times larger THz electric field as the single edge. The multiplexed photo-Dember emitters are superior to the large-area photoconductive emitters when the latter is being biased with an acceleration field below 10 kV/cm or less (see Fig. 4). Besides the higher electric field, the multiplexed photo-Dember emitter also shows a broader spectrum and higher peak frequency than the large-area photoconductive emitter (see inset of Fig. 4).

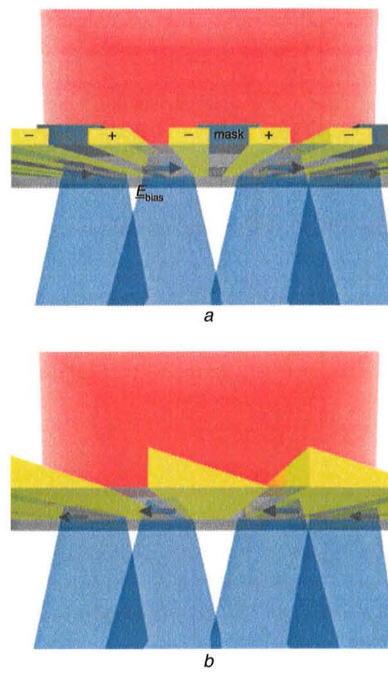

Fig. 3 *Sketch of multiplexed THz emitters based on principle of (Fig. 3a) a photoconductive switch and (Fig. 3b) lateral photo-Dember currents*

In the case of the photoconductive emitter every second gap between the electrodes is masked to avoid destructive interference of the generated THz radiation (indicated by blue areas) in the far field. Analagously, for the photo-Dember emitters, every second carrier gradient is suppressed by wedged metal stripes to achieve unidirectional carrier gradients

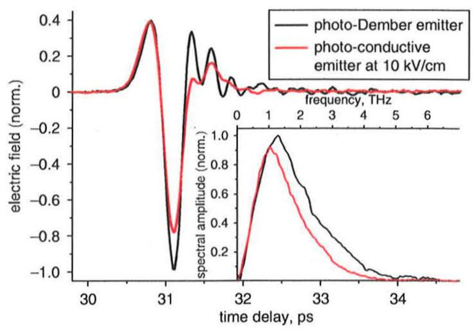

Fig. 4 *Comparison of time transients and Fourier spectra (inset) of large area photoconductive emitter operating at 10 kV/cm bias electric field and multiplexed photo-Dember emitter operating without bias voltage*

Both graphs normalised to corresponding maximum value of photo-Dember emitter

In conclusion, we have discussed two state-of-the-art THz sources, i.e. interdigitated photoconductive emitters, and emitters based on the lateral photo-Dember effect. Multiplexed photo-Dember emitters show a comparable performance to large area photoconductive emitters. Owing to their passive character they are robust against local damage, e.g. short-circuit problems. Also, these emitters do not suffer from substrate or technology related problems leading to high dark currents and associated heating of emitters as in the photoconductive case. The concept of photo-Dember emitters is not limited to certain substrates; hence they are also suitable for excitation with femtosecond fibre lasers.

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