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APPLIED PHYSICS LETTERS **98**, 021114 (2011)

Photo-Dember terahertz emitter excited with an Er:fiber laser

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A terahertz emitter based on the lateral photo-Dember effect is shown to efficiently generate terahertz radiation with a peak frequency of 0.7 THz and an electric field amplitude up to 5 V/cm when excited by 90 fs pulses centered at 1.55 μm. A thin layer of $In_{0.53}Ga_{0.47}As$ grown on InP provides the substrate material in which unidirectional lateral photo-Dember currents are excited. Since photo-Dember terahertz emitters do not require an external bias, they do not suffer from high dark currents limiting the application of biased InGaAs photoconductive terahertz emitters. © *2011 American Institute of Physics*. [doi:10.1063/1.3543627]

Photoconductive sources provide the most efficient way to convert femtosecond laser pulses from an oscillator to terahertz pulses with a central frequency of about 1 THz. In the middle of the 1980s the first photoconductive terahertz experiments were conducted with an Auston switch made on silicon on sapphire (SOS), which was excited by a colliding-pulse passively mode-locked ring dye laser.[1] In the beginning of the 1990s the SOS substrates as well as the dye lasers were replaced with GaAs substrates[2] and Ti:sapphire lasers,[3] respectively. The output spectrum of Ti:sapphire lasers is well matched to the band gap energy of GaAs and ensures excitation near the center of the Brillouin zone. This fact is essential in order to take advantage of the high mobility and the velocity overshoot in the gamma valley.[4,5] For the time being, large-area photoconductive emitters are the most efficient way to generate terahertz radiation in the frequency regime at about 1 THz.[6]

Due to their unique stability, flexibility, and compactness, femtosecond Er:fiber lasers emitting at a central wavelength of 1.55 μm have attracted a lot of attention in the past years for many applications traditionally dominated by femtosecond Ti:sapphire technology.[7,8] Since $In_{0.53}Ga_{0.47}As$ features a band gap energy of 0.74 eV and a lattice constant matched to InP substrates, it is a potential candidate for photoconductive terahertz emitters pumped with 1.55 μm pulses. However, InGaAs has a very low resistivity and hence suffers from high dark currents in biased photoconductive devices.[9] To circumvent this problem the pulses can be frequency doubled to a wavelength of 0.78 μm and GaAs based photoconductive switches can be used, however, with the disadvantage of a strongly reduced average power.[10,11] Another possibility is the implantation of Fe- or Br^+-ions into InGaAs to achieve a higher resistivity.[12,13] Low-temperature growth of InGaAs with additional Be-doping also enhances the resistivity.[9,14]

In this letter we present a terahertz emitter which overcomes the resistivity limit of previous photoconductive switches based on InGaAs. Recently we demonstrated the efficient generation of terahertz radiation by lateral photo-Dember currents induced in GaAs and InGaAs based emitters pumped with a Ti:sapphire laser.[15] The lateral photo-Dember effect is based on ultrafast diffusion currents of electrons when exciting the edge of an opaque material covering the semiconductor. The fast diffusion of electrons into the nonexcited area compared to the slower hole diffusion builds up a space-charge field, i.e., the lateral photo-Dember field. This effect may be enhanced by multiplexing the opaque edges through parallel stripes and breaking the symmetry of the diffusion currents.[15] Here we show that a terahertz emitter based on the lateral photo-Dember effect excited at the fundamental wavelength of an Er:fiber laser of 0.78 μm is an efficient source for terahertz radiation. Conventional $In_{0.53}Ga_{0.47}As$ grown by molecular beam epitaxy or metal-organic chemical vapor deposition may be used because the photo-Dember effect does not rely on external bias or high resistivity of the substrate.

Our experimental setup is based on a commercial multi-branch Er:fiber laser system (Toptica FemtoFiber Pro) providing 90 fs pulses at a center wavelength of 1.55 μm and a repetition rate of 40 MHz. The pulses from one branch are focused into a bulk telecommunication-compatible nonlinear fiber to generate 20 fs gate pulses centered at 1.1 μm.[16] Another branch provides 7.5 nJ pump pulses which are focused onto the photo-Dember emitter using a lens of short focal length (f=50 mm). The generated terahertz radiation propagates through the emitter and is collected and collimated with an off-axis parabolic mirror without using a silicon lens attached to the rear of the emitter. We collinearly combine the terahertz and gate pulses with a nominally undoped silicon wafer (thickness: 500 μm). Both are focused with a second off-axis parabolic mirror onto a 400 μm thick ⟨110⟩-oriented zinc telluride crystal for electro-optic detection. We delay the pump pulses with a translation stage and chop them mechanically at 2.9 kHz to allow lock-in amplification of the terahertz-induced difference in the photocurrents in a balanced pair of photodiodes.[17]

The photo-Dember emitter is prepared on an epitaxial layer (thickness: 1 μm) of $In_{0.53}Ga_{0.47}As$ grown on an InP substrate (thickness: 514 μm). The lateral structure is fabricated by evaporating thin parallel walls of aluminum, which are 250 nm wide and spaced by 3 μm. Subsequently gold is evaporated while varying the angle between the substrate

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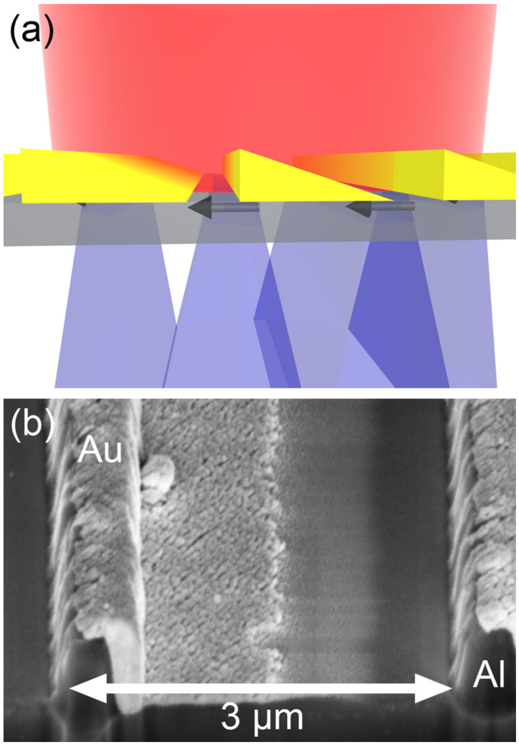

FIG. 1. (Color online) (a) Sketch of the photo-Dember emitter. The laser beam comes from the top (upper area); the generated terahertz radiation is emitted downward (lower area). Every second carrier gradient is suppressed by wedged metal stripes to achieve unidirectional carrier gradients (indicated by the arrows). (b) Scanning electron microscope image of the photo-Dember emitter. On the left an aluminum wall is visible which is covered by a thick gold layer.

and the evaporation source. This results in gold wedges with a width of approximately 2 μm. These structures show a rising slope, i.e., varying from transparent to opaque on one side of the wall, while the other side of the walls exhibit sharp and opaque edges (see Fig. 1). The photo-Dember emitter has a size of 1×1 mm^2. The metal structure on the surface ensures unidirectional lateral carrier gradients after pulsed excitation. All lateral carrier gradients occurring under the sharp edge of each Al wall act as radiating dipoles in the plane of the substrate, which sum up coherently in the far field.

Figure 2(a) depicts a terahertz transient recorded with an excitation power of 260 mW and a spot size of 450 μm on the emitter which corresponds to a maximum excitation density of 1.25×10^{17} cm^{-3}. The polarization of the pump pulse is linear and parallel to the wedges of the emitter.[18] The terahertz transient consists of a single-cycle pulse and minor trailing oscillations due to water vapor in the ambient air. The satellite pulses at 8, 11, and 12 ps arise from reflections of the terahertz pulse in the emitter, the silicon wafer, and the sensor crystal, respectively. The relative difference $\Delta I/I_0$ of the photocurrents measured in both photodiodes amounts to several 10^{-5}. The signal-to-noise level is 40 dB at a 100 ms time constant of the lock-in amplifier. Figure 2(b) shows the corresponding power spectrum of the terahertz transient shown in Fig. 2(a). A time window of 150 ps is Fourier transformed. The spectral coverage of the emitter is 2 THz, while the peak frequency is located at 0.7 THz. We calculate the detector response function in the frequency domain and obtain after an inverse Fourier transform the electric field

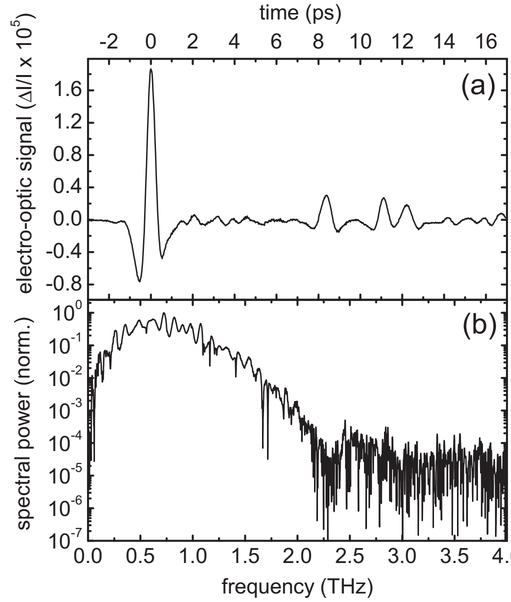

FIG. 2. (a) Terahertz transient generated by exciting a photo-Dember emitter with femtosecond pulses from an Er:fiber laser. Balanced electro-optic detection with a 400 μm thick ZnTe crystal and 20 fs gate pulses results in a maximum relative intensity change of 2.5×10^{-5}, corresponding to a peak-to-peak electric field of 5 V/cm. (b) Fourier transform of the time-domain data of (a) normalized to the peak value at 0.7 THz. The Fabry–Perot-like pattern stems from multiple reflections in the different substrates; the sharp dips are due to ambient water vapor.

amplitude in the time domain.[19] For the data shown in Fig. 1 the electric field amplitude yields a peak-to-peak amplitude of 4.7 V/cm.

Next we test the dependence of the terahertz emission on excitation powers and spot sizes. We use neutral density filters to vary the excitation power and translate the focusing lens along the direction of propagation to change the pump spot size. Figure 3 depicts the absolute peak-to-peak amplitudes of $\Delta I/I_0$ for three different spot sizes (110, 230, and 450 μm) and eight different optical power levels. The terahertz amplitude increases with increasing power and spot size and saturates eventually. This saturation arises from the finite density of states in the conduction band of the InGaAs layer. The higher terahertz amplitude with increased spot size shows how this saturation can be circumvented by scaling up the emitter area.

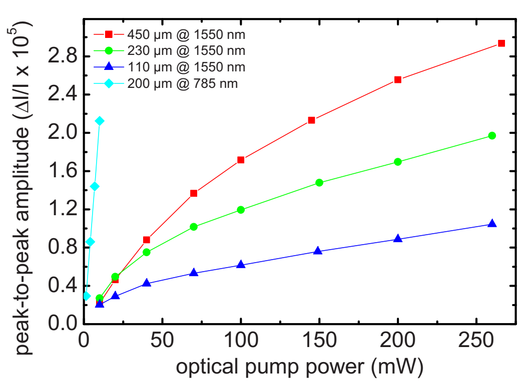

FIG. 3. (Color online) Power dependence for three different spot sizes at the fundamental wavelength of 1.55 μm and for one spot size at the frequency-doubled wavelength of 0.78 μm. The peak-to-peak amplitude is in units of the relative intensity changes in the electro-optic detection which remained unchanged for all excitation conditions.

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We perform measurements with frequency-doubled pump light under *unchanged* gate conditions in order to compare the results for 1.55 μm-excitation with 0.78 μm-excitation wavelength. We use a 1.5 mm thick beta-barium borate crystal with critical phase matching to generate 75 fs pump pulses centered at 0.78 μm. The polarization of the frequency-doubled light is perpendicular to the wedges of the emitter.[20] The power dependence for excitation at 0.78 μm and a spot size of 200 μm is shown in Fig. 3. For similar spot sizes and pump powers the emitted terahertz electric field is about eight times larger when using pulses centered at 0.78 μm compared to pulses centered at 1.55 μm.[20] However, the maximum terahertz amplitude generated with a similar spot size and maximum power of the fundamental is comparable to the maximum value obtained at 0.78 μm. We attribute the stronger terahertz emission to the much smaller absorption coefficient of 8000 cm^{-1} at 1.55 μm compared to 55 000 cm^{-1} at 0.78 μm.[21] Using the Lambert–Beer law and neglecting reflection, about 99.5% of 0.78 μm light is absorbed in a 1 μm thick InGaAs layer, while only 55% of 1.55 μm light is absorbed. As a consequence, the carrier gradient generated is smaller leading to a reduced lateral photo-Dember field. For the largest spot size used for 1.55 μm excitation the terahertz amplitude is about 40% larger than the largest amplitude achieved with 0.78 μm excitation.

Finally, we note that the photo-Dember emitters do not require a careful focusing of the exciting laser on a few micrometers sized photoconductive gap, because the position of the excitation spot on the millimeter-sized emitter is not critical, and no (silicon) lens is used for outcoupling. Combined with the turnkey nature of femtosecond Er:fiber lasers this fact renders the photo-Dember emitters particularly well suited for robust and easy to use systems for terahertz time-domain spectroscopy. For low-cost applications a single-branch Er:fiber laser could also be used by splitting off a fraction of the pump pulses as gate pulses. A double-laser based scanning system based on asynchronous optical sampling[10,22,23] could strongly decrease the measurement time to achieve a signal-to-noise ratio of 60 dB within 100 s.

In summary, we have demonstrated efficient terahertz generation in InGaAs photo-Dember emitters excited by femtosecond pulses from a compact Er:fiber system. It is shown that the peak field of the emitted terahertz transients is currently limited by the absorption coefficient of InGaAs at 1.55 μm. As terahertz emitters based on the lateral photo-Dember effect are not limited by restrictions given by the application of a static bias field, the efficiency of photo-Dember emitters can be further increased using semiconductors with even smaller band gaps like InAs or InSb.

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