Quantitative comparison of terahertz emission from (100) InAs surfaces and a GaAs large-aperture photoconductive switch at high fluences

Matthew Reid and Robert Fedosejevs

InAs has previously been reported to be an efficient emitter of terahertz radiation at low excitation fluences by use of femtosecond laser pulses. The scaling and saturation of terahertz emission from a (100) InAs surface as a function of excitation fluence is measured and quantitatively compared with the emission from a GaAs large-aperture photoconductive switch. We find that, although the instantaneous peak radiated terahertz field from (100) InAs exceeds the peak radiated signals from a GaAs large-aperture photoconductive switch biased at 1.6 kV/cm, the pulse duration is shorter. For the InAs source the total energy radiated is less than can be obtained from a GaAs large-aperture photoconductive switch. © 2005 Optical Society of America

OCIS codes: 320.7110, 320.7130.

Over the past two decades, high-brightness terahertz (THz) sources have been developed with ultrafast laser sources to excite photoconductive switches,[1] to excite transient currents on semiconductor surfaces,[2] and to excite nonlinear processes in materials.[2,3] As application areas grow for THz technology, the need for efficient sources is growing.

InAs THz emitters were originally reported to be reasonably efficient sources of far-infrared radiation[4] and have since proven to be relatively bright emitters of THz radiation, especially under the influence of a magnetic field.[5–7] These studies were carried out at low fluences of the order of a microjoule per square centimeter or less, below the saturation fluence of InAs.

In this paper we investigate the efficiency of InAs as a high-power THz emitter under high excitation fluence. The GaAs large-aperture photoconductive switch (LAPCS) has been used in the past to generate the highest reported conversion efficiency from optical to pulsed THz radiation[8] and has been used as a benchmark for efficiency of THz emitters.[9] In this paper such a GaAs LAPCS is used for comparison to gauge the overall conversion efficiency of InAs. Scaling of emission with excitation fluence and saturation of emission is presented, and a quantitative comparison with a GaAs LAPCS is reported.

The experimental setup is shown in Fig. 1. A regeneratively amplified Ti:sapphire laser system (Spectra-Physics Hurricane) is used as a source, operating at a center wavelength of 800 nm, at a 1-kHz repetition rate, with a maximum pulse energy of 750 μJ and a pulse width of 130 fs (Gaussian FWHM). The beam is split into pump (92%) and probe (4%) beams by use of a wedged window. The probe is delayed with respect to the pump by an optical delay line, allowing time-resolved mapping of the THz field. A variable attenuator ($\lambda/2$ plate and polarizer) is used in the pump beam to vary the fluence. The THz radiation from the emitter is collected and imaged onto the detector by four $F/2$ parabolic mirrors in an f-2f-f geometry to minimize frequency-dependent focusing effects[10–12] and allow a direct comparison of emitted THz fields between the two emitters. We use the four parabolic mirrors to attain an intermediate focal plane for testing samples, which is not used for the present study. To detect the THz radiation, the probe is collinearly propagated through a 1-mm-thick (110) ZnTe electro-optic crystal, with the THz field. This induces a polarization modulation, which we analyze using a polarization bridge ($\lambda/4$ plate and Wollaston prism), with the differential photodiode signal detected with a lock-in amplifier at the optical

---

The authors are with the Department of Electrical and Computer Engineering, University of Alberta, Alberta, Edmonton T6G 2V4, Canada. The e-mail address for R. Fedosejevs is rfed@ece.ualberta.ca.

Received 3 August 2004; revised manuscript received 3 August 2004; accepted 11 September 2004.

0003-6935/05/010149-05$15.00/0

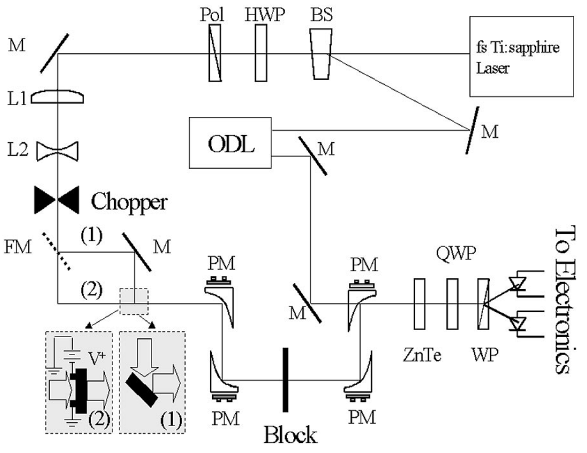

Fig. 1. Schematic diagram of the THz system used in the experiments. FM, flip mirror; Pol, polarizer; BS, wedged beam splitter; PM, parabolic mirrors; QWP and HWP, quarter- and half-wave plates, respectively; WP, Wollaston prism; L1 and L2, +50- and −15-cm focal-length lenses; Block, visibly opaque beam block to block the fundamental; and ODL, optical delay line. The emitter used is either an externally biased GaAs photoconductive switch or a (100) oriented InAs surface. (1) and (2) represent beam paths to InAs and GaAs emitters, respectively.

chopping frequency of approximately 330 Hz. The orientation of the ZnTe crystal is chosen to maximize the electro-optic signal.[13] The GaAs emitter used is constructed on a high-resistivity GaAs substrate (the carrier concentration and hall mobility specified by the manufacturer are $n_c = 1.5 \times 10^{-7}\ \mathrm{cm}^{-3}$ and $\mu_H = 3890\ \mathrm{cm}^2\ V^{-1}\ s^{-1}$, respectively). Silver paint was used to define electrodes with a gap spacing of 0.19 cm and biased at 300 V (1.6 kV/cm). The GaAs emitter is illuminated at normal incidence and the transmitted THz beam is collected. The InAs emitter is a (100) oriented, undoped, *n*-type InAs sample ($n_c = 1.9 \times 10^{-16}\ \mathrm{cm}^{-3}$, $\mu_H = 2.5 \times 10^4\ \mathrm{cm}^2\ V^{-1}\ s^{-1}$) that is illuminated at a 45-deg angle of incidence. We telescoped the pump beam to a $1/e^2$ intensity beam diameter of 2.85 ± 0.05 mm for both emitters using a pair of lenses as shown in Fig. 1.

The mechanism responsible for radiated THz fields from (100) InAs at high excitation fluence was recently reported to be primarily a result of surface optical rectification,[14] with only minor contributions from carrier-related effects. We determined this by examining the *s*-polarized THz emission from the InAs wafer, where the contributions from carrier-related effects must vanish. Therefore the dominant emission mechanism at high fluences is expected to be optical rectification at the surface. For that case, the maximum radiated THz signal was *p* polarized and obtained for a *p*-polarized pump beam, regardless of the sample orientation. In this paper the orientation of the crystal is such that the projection of the *p*-polarized pump beam on the (100) plane of the InAs crystal is at 45 deg relative to both the [010] and [001] crystallographic axes, and the *p*-polarized THz beam is collected. Initial measurements of the saturation of the signals from InAs were carried out in the absence of magnetic fields.

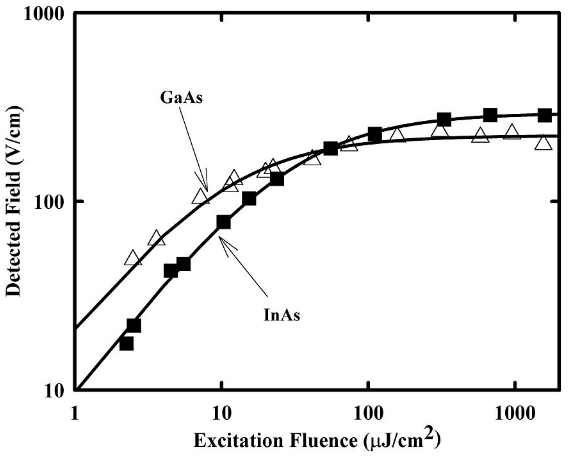

Fig. 2. Detected THz field as a function of excitation fluence for the two emitters used. Open triangles, signals from a GaAs LAPCS biased at 1.6 kV/cm; filled squares, signals from (100) InAs. Solid curves, fit to the data.

To determine the efficiency and saturation of the two emitters, the scaling of the THz emission with optical excitation fluence was measured. Here the fluence is calculated as the full energy of the pump beam before striking the surface of the emitter, divided by the $1/e^2$ (intensity) beam area of $0.064 \pm 0.003\ \mathrm{cm}^2$. The GaAs LAPCS is oriented in a transmission geometry, such that the pump beam illuminates the switch at normal incidence, whereas the InAs sample is unbiased with the bare (100) surface oriented at 45 deg to the pump beam as shown in Fig. 1. The resultant measured emitted field as a function of the incident fluence is presented in Fig. 2. The THz signal from both emitters is observed to saturate as the fluence is increased. The radiated field is well described by the simple saturation formula $E_{\mathrm{THz}}^{\mathrm{pk}} = BF/(F + F_{\mathrm{sat}})$, where B is a scaling constant, F is the excitation fluence, and F_{sat} is the saturation fluence. The solid curves in Fig. 2 are the fits of this equation to the data, and the values for B are 294 and 223 V/cm and those for F_{sat} are 29.3 and 9.6 $\mu\mathrm{J/cm}^2$ for InAs and GaAs, respectively. The value for the saturation flux of the GaAs obtained here is within 30% of the more recently reported results for the saturation flux from a GaAs LAPCS.[9,15,16] In our case the GaAs aperture is overfilled. However, in most reports on saturation behavior of the GaAs LAPCS, the pump beam diameter is comparable to the aperture dimension.

From Fig. 2 it is clear that the peak radiated field from the (100) InAs emitter is larger in the saturated regime and reaches a saturated field approximately 30% higher than that for the GaAs LAPCS. In addition, the saturation fluence for InAs is almost 3 times larger than that for the GaAs LAPCS.

With quantification of the scaling of both emitters with excitation fluence, the question of which emitter most efficiently converts optical to far-infrared en-

Table 1. Parameters Used in the Estimation of Optical to Far-Infrared Conversion Efficiency

Property	GaAs	InAs	Description
System loss	1.44	1.44	E field attenuation factor of beam block
Fresnel loss	1.42	1.31	E field Fresnel reflection losses
τ (ps)	1.54	0.79	Average measured $1/e$ pulse widths
THz spot (cm)	0.342	0.245	Measured $1/e$ THz field diameters
B (V/cm)	223	294	Measured saturation amplitude
F_{sat} (μJ/cm^2)	9.6	29.3	Measured saturation fluence
E (μJ)	0.82 FA	FA	Integral of $F(A)$ over the excitation area
A (cm^2)	0.064	0.064	$1/e^2$ intensity beam area of excitation beam

ergy can be examined. We can estimate the total energy in the THz pulses and compute an estimate for the overall conversion efficiency. The method is outlined as follows. The conversion efficiency η is defined by

$$\eta = \left(\frac{W_{\mathrm{THz}}}{W_{\mathrm{inp}}}\right), \tag{1}$$

where the estimated THz pulse energy is

$$W_{\mathrm{THz}} \approx \frac{\tau A\,|E_{\mathrm{THz}}^{\mathrm{pk}}|^2}{2\eta_0}. \tag{2}$$

Here W represents energy, τ is the $1/e$ (electric field) THz pulse width, A is the area of the THz beam at the detector, $E_{\mathrm{THz}}^{\mathrm{pk}}$ is the peak radiated THz field, and η_0 is the impedance of free space. Detected fields are corrected for Fresnel reflection at the emitter and detector, T_R, and system transmission losses T_S as

$$|E_{\mathrm{THz}}^{\mathrm{pk}}| \approx |E_{\mathrm{THz}}^{\mathrm{pk}}|_{\mathrm{measured}} T_R T_S. \tag{3}$$

We compute the input optical energy by integrating over the emission aperture:

$$W_{\mathrm{inp}} = \iint\limits_{\mathrm{aperature}} F_{\mathrm{opt}}^{\mathrm{excite}}(x,\, y)\mathrm{d}x\mathrm{d}y. \tag{4}$$

The experimental values used are given in Table 1. We measured the THz beam waist at the detector for the two emitters by scanning the THz beam laterally across the optical probe beam, which is less than 100 μm in diameter, and by measuring the $1/e$ THz electric field diameter. The system loss factor was calculated from the transmission spectrum of the optically opaque beam block used to block the laser radiation from hitting the detector, which had a flat frequency response over the bandwidth of both emitters.

Using the values in Table 1, and computing the conversion efficiency as outlined above, we obtained the results presented in Fig. 3.

Note that the conversion efficiency for the GaAs is much larger than for InAs because of a larger THz beam waist at the detector and a longer pulse width. The larger THz beam waist at the detector is likely a result of diffraction from the emitting aperture because of the longer emission wavelengths and the reduced emitting aperture for GaAs compared with InAs. For our GaAs LAPCS, the maximum conversion efficiency, at a bias field of 1.6 kV/cm, was approximately 1.9×10^{-5}, whereas for InAs it was 2.1×10^{-6}. The best reported conversion efficiency for a GaAs LAPCS was 1.6×10^{-3} at a bias field of 10.6 kV/cm.[8] Given that the THz pulse energy scales quadratically with the bias field,[17] then the maximum conversion efficiency expected from our LAPCS at 10.6 kV/cm would be 0.8×10^{-3}, which is a factor of 2 less than reported by You *et al.*[8] This discrepancy is possibly a result of our not including a group-velocity mismatch in the ZnTe electro-optic detector (thermal detection was used by You *et al.*) and diffraction losses because of the limited collection angle in our system. The measured frequency spectrum from the two emitters, at an excitation fluence of 1 mJ/cm^2, is presented in Fig. 4, from which it is also clear that the InAs emitter is better suited to producing higher-frequency THz radiation (more efficient above 0.75 THz).

Given that the emitter aperture for the LAPCS is 0.19 cm laterally, and the collection is $F/2$, the matching frequency is 0.32 THz for a diffraction-

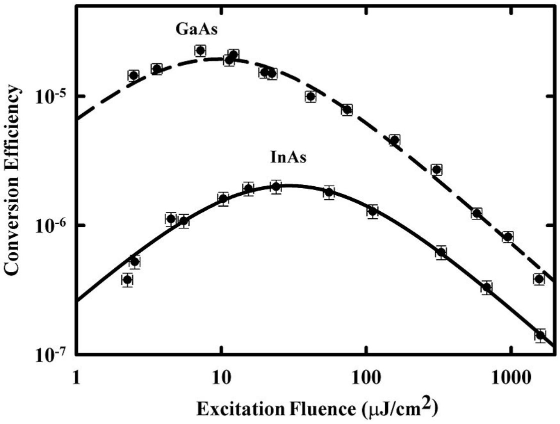

Fig. 3. Estimated conversion efficiencies based on Eqs. (1)–(4) with measured saturation values. The dashed curve is for the GaAs LAPCS at a 1.6-kV/cm bias, and the solid curve is for (100) InAs. The data points are from Fig. 2, with their associated experimental error.

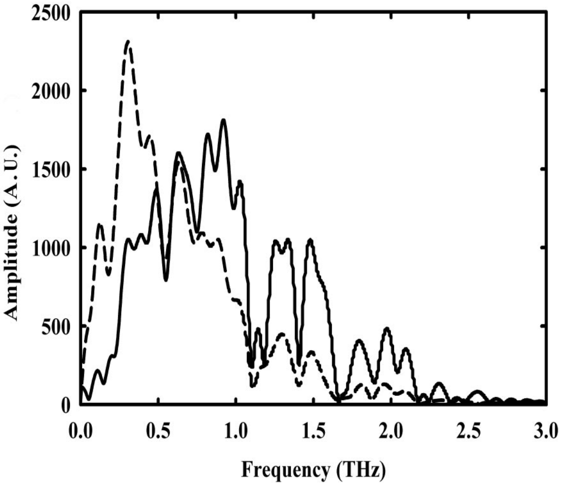

Fig. 4. Frequency spectrum of THz fields at the detector from the GaAs LAPCS biased at 1.6 kV/cm (dashed curve) and the (100) InAs (solid curve) at an excitation fluence of 1 mJ/cm^2.

limited beam diffracting from the aperture and exactly filling the $F/2$ collection optics, below which we expect the signal will be attenuated. The peak of the measured THz spectra occurs at 0.33 THz (see Fig. 4), which agrees well with the expectation for a diffraction-limited beam. Focusing the THz field from a LAPCS with minimal collection angle losses results in a spectrum with a peak at approximately 0.1 THz or less.[15] With larger-aperture GaAs LAPCS emitters measured in our laboratory, we have also observed a peak emission frequency close to 0.1 THz. An approximate estimate of the truncation of the spectrum leading to the 0.3-THz peak emission frequency observed here indicates that approximately half of the emitted radiation is lost because of diffraction losses on the optical components. Thus our observed peak efficiency is consistent with the peak value reported by You *et al.*[8] It is clear that in this regime the large conversion efficiency for GaAs is a result of energy extracted from the electric bias field and not from the energy in the laser pulse itself.

Although the conversion efficiency for the GaAs LAPCS in Fig. 3 can be scaled to higher bias voltages, the unbiased emission from (100) InAs cannot be scaled further, making it much less efficient at converting optical to far-infrared energy than the GaAs LAPCS. However, the application of a magnetic field at low excitation fluences has been shown to increase the THz emission significantly. In fact, the THz emission power was shown to scale quadratically with the applied magnetic field,[4] saturating above approximately 3 T.[18–20] The enhancement in the emission has been ascribed to the deflection of the photocarrier diffusion current, causing a larger component parallel to the surface that radiates more efficiently and hence increases output radiation.[5] For the case in which the THz signal is predominantly a result of surface optical rectification, an applied magnetic field would not have the same dramatic effect. We measured the effect of a 0.7-T magnetic field, which results in no more than a 20% change in the peak radiated field when the InAs is excited at a fluence of approximately 1 mJ/cm^2. Assuming quadratic power scaling with the magnetic field, that portion of the THz field that is increasing as the square of the magnetic field is estimated to produce at most a 1.7 times increase in THz field strength (3 times in power) in the present polarization configuration, for a field of 3T at a fluence of 1 mJ/cm^2. Since the optimal conversion efficiency is obtained for operation at F_{sat} (see below), the effect of the magnetic field around the saturation fluence is the important parameter. Recent results indicate that above approximately 0.2 μJ/cm^2, the effect of the magnetic field is not as dramatic as at lower fluences.[21] In Ref. 21, results for an applied magnetic field of +1.6 T amounted to a constant increase in radiated THz power from InAs surfaces of approximately 2 times, above excitation fluences of approximately 0.2 μJ/cm^2. With the reasoning stated above, the expected increase at 1.6 T (based on our observation of an approximate 20% increase in signal at 0.7 T) would be a 1.45 times increase in electric field, or a 2 times increase in power, consistent with that reported by Takahashi *et al.*[21] Our conclusion is that, although the power radiated from the GaAs LAPCS can be further increased with the application of higher bias fields, the InAs is not expected to be enhanced by more than a factor of 3, even at large magnetic fields. The reason for this is simply that the saturation flux for the emission does not change substantially, nor does the maximum of the radiated field, with the application of a strong magnetic field.

An upper bound on the radiated far-infrared energy from a LAPCS can be estimated, assuming that the maximum radiated field is given by the bias field. Using the results of Darrow *et al.*,[17] in the near field we obtain the peak radiated THz field by

$$E_{\text{rad,THz}}^{\text{near field}} = E_b\left(\frac{F}{F + F_{\text{sat}}}\right), \tag{5}$$

where F_{sat} is the saturation flux. Using Eq. (1) with $E_{\text{excite}} = AF$, with A the area of the emitter that equals the size of the emitted THz beam, we obtain

$$\eta = \frac{\tau E_b{}^2}{2F\eta_0}\left(\frac{F}{F + F_{\text{sat}}}\right)^2. \tag{6}$$

Also, noting that the maximum conversion efficiency occurs at F_{sat}, using $\tau \sim 1$ ps and $F_{\text{sat}} = 9.6\ \mu\text{J/cm}^2$, we obtain an upper bound on the conversion efficiency at $E_b = 10$ kV/cm of

$$\eta = \frac{\tau E_b{}^2}{2\eta_0}\left(\frac{1}{4F_{\text{sat}}}\right) = 3.2 \times 10^{-3}. \tag{7}$$

This is approximately two times bigger than reported by You *et al.*[8] and four times bigger than reported here. Again, the possible reasons that we observed a lower conversion efficiency may be because we did not include the effects of group-velocity mismatch in the detection crystal and we lost a significant portion of the THz signal outside of the collection angle of the imaging system. It is clear, nonetheless, that the generated THz energies are in the range of the theoretical limit.

The magnitude of the emission from an InAs and a GaAs LAPCS emitter was measured as a function of irradiation fluence. Both emitters saturated and could be fit by use of a simple saturation equation, with observed saturation fluences in terms of incident laser fluences of 29.3 and 9.6 $\mu J/cm^2$ for the InAs and GaAs emitters, respectively. Correcting the detected peak radiated THz fields for Fresnel and system losses, the peak conversion efficiencies were estimated to be 2.1×10^{-6} and 1.9×10^{-5} for InAs and GaAs (1.6-kV/cm bias), respectively. By use of the expected quadratic scaling with the bias field up to the breakdown voltage of GaAs of 10 kV/cm, the efficiency of the GaAs LAPCS can be considerably enhanced relative to that of unbiased InAs and approaches the theoretically expected limit based on the bias field and saturation flux.

We gratefully acknowledge financial support provided by MPB Technologies, Inc. and the National Sciences and Engineering Research Council of Canada.

References

1. D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting hertzian dipoles," Appl. Phys. Lett. **45,** 284–286 (1984).
2. X.-C. Zhang and D. H. Auston, "Optoelectronic measurement of semiconductor surfaces and interfaces with femtosecond optics," J. Appl. Phys. **71,** 326–338 (1992).
3. B. B. Hu, X.-C. Zhang, D. H. Auston, and P. R. Smith, "Free-space radiation from electro-optic crystals," Appl. Phys. Lett. **56,** 506–508 (1990).
4. N. Sarakura, H. Ohtake, S. Izumida, and Z. Liu, "High average-power THz radiation from femtosecond laser-irradiated InAs in a magnetic field and its elliptical polarization characteristics," J. Appl. Phys. **84,** 654–656 (1998).
5. C. Weiss, R. Wallenstein, and R. Beigang, "Magnetic-field-enhanced generation of terahertz radiation in semiconductor surfaces," Appl. Phys. Lett. **77,** 4160–4162 (2000).
6. R. McLaughlin, A. Corchia, M. B. Johnston, Q. Chen, C. M. Ciesla, D. D. Arnone, G. A. C. Jones, E. H. Linfield, A. G. Davies, and M. Pepper, "Enhanced coherent terahertz emission from indium arsenide in the presence of a magnetic field," Appl. Phys. Lett. **76,** 2038–2040 (2000).
7. J. N. Heyman, P. Neocleous, D. Hebert, P. A. Crowell, T. Mueller, and K. Unterrainer, "Terahertz emission from GaAs and InAs in a magnetic field," Phys. Rev. B. **64,** 0852021–0852027 (2001).
8. D. You, R. R. Jones, P. H. Bucksbaum, and D. R. Dykaar, "Generation of high-power sub-single-cycle 500-fs electromagnetic pulses," Opt. Lett. **18,** 290–292 (1993).
9. T. Löffler and H. G. Roskos, "Gas-pressure dependence of terahertz-pulse generation in a laser-generated nitrogen plasma," J. Appl. Phys. **91,** 2611–2614 (2002).
10. A. Gürtler, C. Winnewisser, H. Helm, and P. U. Jepsen, "Terahertz propagation in the near field and far field," J. Opt. Soc. Am. A. **17,** 74–83 (2000).
11. D. You and P. H. Bucksbaum, "Propagation of half-cycle far infrared pulses," J. Opt. Soc. Am. B. **14,** 1651–1655 (1997).
12. E. Budiarto, N.-W. Pu, S. Jeong, and J. Bokor, "Near-field propagation of terahertz pulses from a large-aperture antenna," Opt. Lett. **23,** 213–215 (1998).
13. P. C. M. Planken, H.-K. Nienhuys, H. J. Bakker, and T. Wenckebach, "Measurement and calculation of the orientation dependence of terahertz pulse detection in ZnTe," J. Opt. Soc. Am. B. **18,** 313–317 (2001).
14. M. Reid and R. Fedosejevs, "Terahertz emission from (100) InAs at high excitation fluences," Appl. Phys. Lett. (to be published).
15. T. Hattori, K. Tukamoto, and H. Nakatsuka, "Time-resolved study of intense terahertz pulses generated by a large-aperture photoconductive antenna," Jpn. J. Appl. Phys. **40,** 4907–4912 (2001).
16. G. Rodriguez and A. J. Taylor, "Screening of the bias field in terahertz generation from photoconductors," Opt. Lett. **21,** 1046–1048 (1996).
17. J. T. Darrow, X.-C. Zhang, and D. H. Auston, "Saturation properties of large-aperture photoconducting antennas," IEEE J. Quantum Electron. **28,** 1607–1616 (1992).
18. H. Takahashi, Y. Suzuki, A. Quema, M. Sakai, T. Yano, S. Ono, N. Sarakura, M. Hosomizu, T. Tsukamoto, G. Nishijima, and K. Watanabe, "Magnetic-field-induced enhancement of thz-radiation power from femtosecond-laser-irradiated InAs up to 27T," Jpn. J. Appl. Phys. **42,** L532–L534 (2003).
19. H. Takahashi, Y. Suzuki, M. Sakai, S. Ono, N. Sarakura, T. Sugiura, T. Hirosumi, and M. Yoshida, "Significant enhancement of terahertz radiation from InSb by use of a compact fiber laser and an external magnetic field," Appl. Phys. Lett. **82,** 2005–2007 (2003).
20. M. Hangyo, M. Migita, and K. Nakayama, "Magnetic field and temperature dependence of terahertz radiation from InAs surfaces excited by femtosecond laser pulses," J. Appl. Phys. **90,** 3409–3412 (2001).
21. H. Takahashi, A. Quema, R. Yoshioka, S. Ono, and N. Sarakura, "Excitation fluence dependence of terahertz radiation mechanism from femtosecond-laser-irradiated InAs under magnetic field," Appl. Phys. Lett. **83,** 1068–1070 (2003).