High average-power THz radiation from femtosecond laser-irradiated InAs in a magnetic field and its elliptical polarization characteristics

Nobuhiko Sarukura,[a] Hideyuki Ohtake, Shinji Izumida, and Zhenlin Liu
Institute for Molecular Science (IMS), Myodaiji, Okazaki 444-8585, Japan

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The THz-radiation power from bulk InAs irradiated with femtosecond optical pulses is significantly enhanced and reaches 650 μW in a 1.7-T magnetic field with 1.5-W excitation power. The THz-radiation power is related almost quadratically both to the magnetic field and excitation laser power. We have also found that the power of the THz-radiation from an InAs sample in a magnetic field is over one order of magnitude higher than that from GaAs. Additionally, a dramatic change of ellipticity is observed, and the spectra of the horizontal and vertical polarization components are found to differ. © *1998 American Institute of Physics.* [S0021-8979(98)09313-X]

Various THz-radiation sources have been intensively studied including photoconductive switches irradiated with ultrashort optical pulses,[1–5] two different color cw lasers,[6] or parametric oscillators.[7] The average power of optical short-pulse excited THz-radiation source was at most mW level, mostly limited by the electric breakdown of the photoconductive antennas.[4] For applications to sensing or imaging[8] and time-resolved spectroscopy in the far-infrared region,[9] an intense, compact, and simple light source is required. Zhang *et al.* reported quadratic dependence of the laser induced THz-radiation on the magnetic field.[10] There was also a report of Landau-level contribution.[11] In this communication, we report the significant enhancement of THz-radiation power from semiconductors irradiated with femtosecond optical pulses. The power reaches 650 μW in a 1.7-T magnetic field with 1.5-W excitation power. This is the highest average power ever achieved in THz radiation at around a 100-MHz repetition rate. A 200-μW average power was obtained even using a compact 1-T permanent magnet. Moreover, we found an interesting change of ellipticity of the magnetic field.

The experimental setup for the THz-radiation emitter in a magnetic field is shown in Fig. 1. A mode-locked Ti:sapphire laser delivered 70-fs pulses at 800 nm with an 80-MHz repetition rate using 1.5-W average power for the excitation. The sample was nondoped bulk InAs with a (100) surface. The conduction type of nondoped bulk InAs was slightly n, and the carrier density of this InAs was 3.0×10^{16} cm^{-3}. The InAs sample itself is highly reflective, unlike transparent GaAs. The reflectivity of the THz radiation was measured to be approximately 70% for a 45 degree incidence angle. Therefore, the THz radiation was totally generated in the reflection direction. This highly reflective nature of InAs is preferable for the THz-radiation emitter in two points. First, it eliminates the rear surface reflection of the radiation that normally produces interferometric structures in the spectrum. Second, it enhances THz radiation due to the reflection from the irradiated surface itself. A liquid-helium-cooled InSb bolometer with sub-nW sensitivity (QMC Model QFI/2BI) was provided for detection. The advantage of the bolometer for this measurement is the easiness of the collection of the beam and the lack of timing or optical delay control. The InAs sample was placed 45° to the magnetic field, and the excitation laser was parallel to the magnetic field. The excitation laser irradiated the sample with a 2-mm diameter spot. This sufficiently large excitation area is advantageous for reducing the diffraction effect and decreases the possibility of damaging the emitter even for such high average-power excitation. In this geometry, the THz radiation was detected even without the magnetic field, similar to GaAs in Ref. 12. In this case, the mechanism of the THz radiation was attributed to the carrier motion in the surface depletion electric field.[13,14] The THz-radiation power dependence on the excitation power was measured in a 1.7-T magnetic field as shown in Fig. 2. The radiation power exhibits almost quadratic dependence on the excitation power, and saturation of the THz-radiation power was observed when excitation power exceeded 500 mW. For cw Ti:sapphire laser excitation without mode locking at the same wavelength, the same

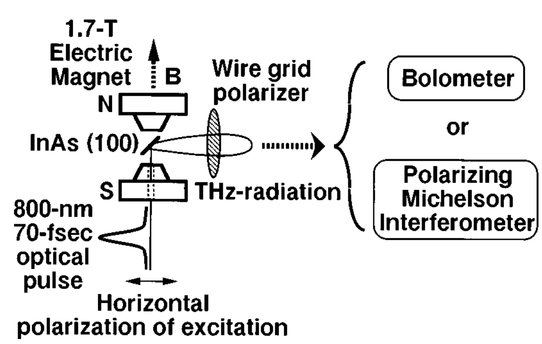

FIG. 1. The experimental setup for THz-radiation emitter in a magnetic field. A mode-locked Ti:sapphire laser delivered 70-fs pulses at 800 nm for excitation. The sample was nondoped bulk InAs with a (100) surface. A liquid-helium-cooled InSb bolometer with calibrated sensitivity was provided for detection. The InAs sample was placed at 45° to the magnetic field, and the excitation laser was parallel to the magnetic field. The maximum field of the electric magnet was 1.7 T, and the magnetic field can also be applied in the opposite direction. For the polarization-resolved spectral measurement, a wire-grid polarizer was inserted into the optical path.

[a]Electronic mail: saru@ims.ac.jp

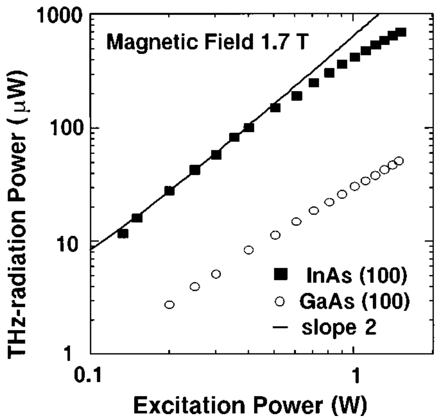

FIG. 2. Excitation-power dependence of THz-radiation power. THz radiation from InAs (circle) increase rapidly as excitation-power increases. THz radiation from GaAs (square) is also shown for comparison. The dotted line indicates slope 2.

average power, and the same optical geometry, this intense THz radiation totally disappears. We have also found that the power of the THz radiation from an InAs sample in a magnetic field is over one order of magnitude higher than that from nondoped GaAs with a (100) surface in the same conditions shown in Fig. 2. The magnetic-field dependence of the THz-radiation power is shown in Fig. 3. The radiation power is quadratically related to the higher magnetic field region as was the case for GaAs.[10] Owing to this quadratic dependence on the magnetic field and the excitation power, the total THz-radiation power reaches 650 μW in a 1.7-T magnetic field with 1.5-W excitation power measured by a liquid-helium-cooled InSb bolometer with calibrated sensitivity. This THz-radiation average power at around a 100-MHz repetition rate is to our knowledge the highest ever obtained. Moreover, 200-μW average power was obtained even using a compact 1-T permanent magnet instead of the 1.7-T large electric magnet. The accuracy of the power calibration done by the manufacturer is estimated to be less than 10% at most, and there may also be collection loss of the radiation by the focusing optics to the bolometer.

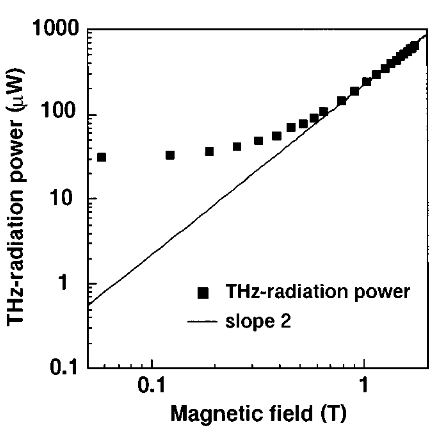

FIG. 3. Magnetic field dependence of THz-radiation power. THz radiation from InAs (solid squares) increases dramatically as the magnetic field increases. The solid line indicates slope 2.

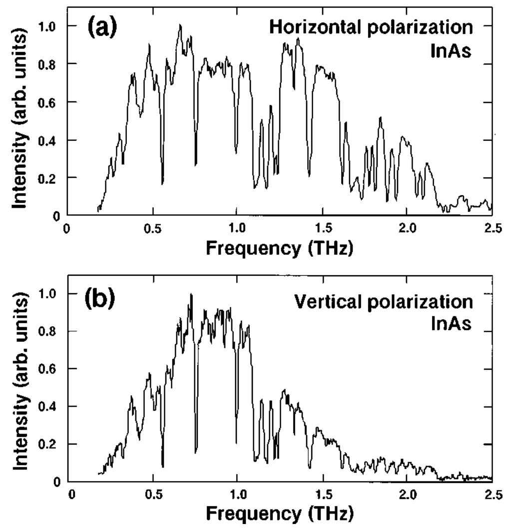

FIG. 4. Spectrum of THz radiation from InAs in a 1.7-T magnetic field obtained by Fourier transformation of the autocorrelation using a polarizing Michelson interferometer: (a) Horizontal polarization, (b) vertical polarization. The dips correspond to water vapor absorption.

The spectra of the horizontal and vertical components of the THz radiation were obtained by a polarizing Michelson interferometer with the bolometer as shown in Fig. 1. To select the horizontal and vertical components of THz radiation, a free-standing, 30-μm spaced metal wire-grid polarizer was inserted into the optical path. The spectral shape for the different magnetic field was almost identical. However, the spectral shapes for different polarization components are significantly different, and the radiation peaks were approximately 1 and 0.7 THz for horizontal and vertical polarization components as shown in Figs. 4(a) and 4(b). The higher frequency spectrum is enhanced in horizontal polarization components. The dips in the spectrum correspond to the absorption of the water vapor in the path of the THz radiation in air.[15]

For this optical configuration, the ellipticity[16] of the THz radiation was measured for the different magnetic field using a wire-grid polarizer as shown in Fig. 5(a). Such ellipticity can easily be evaluated by the transmission power measurements using a polarization-insensitive bolometer through this wire-grid polarizer. In the zero field, the radiation was completely polarized parallel to the magnetic field. At around 0.25 T, the radiation polarization became nearly circular. In higher field, it returned to close to linear polarization as shown in Fig. 5(b). If the magnetic field was applied in the opposite direction, the phase difference became opposite. This elliptical polarization nature can be attributed to the vertical and horizontal projections of the photocurrent in semiconductor surface caused by the magnetic field and surface depletion electric field as described in Ref. 8. Supporting this explanation, the ellipticity dependence on magnetic field is much less for GaAs with a larger electron mass (0.063 m_0)[17] than for InAs with a smaller electron mass (0.022 m_0)[17] as shown in Fig. 5(c). Due to this smaller mass, the photoelectrons in InAs will be accelerated easier by the external magnetic field and the surface depletion electric field, and the THz-radiation power from InAs is much higher

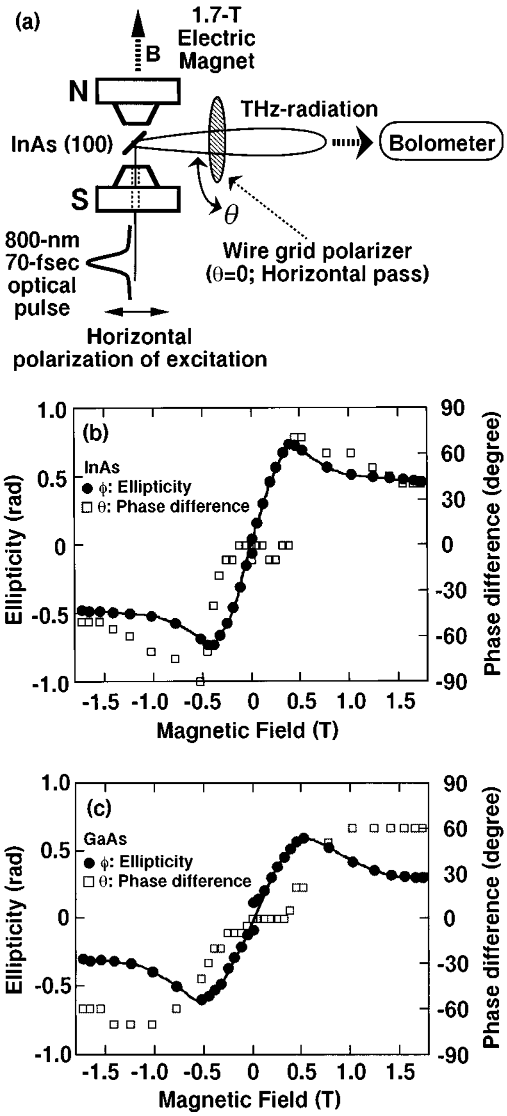

FIG. 5. (a) Experimental setup for evaluating ellipticity of THz radiation. Ellipticity is defined by inverse tangent of the ratio of the electric field along the minor and the major axis. This parameter shows deviation of an ellipse from a circle. The phase difference is defined by the rotation of the major axis from the horizontal plane; (b), (c) ellipticity of THz radiation from GaAs (b) and InAs (c). In both samples, the ellipticity changes dramatically, and InAs is more sensitive to the magnetic field.

than that from GaAs. Since the carrier motion in the vertical and horizontal directions is not identical under this optical configuration, the observed spectral difference in the horizontal and vertical polarization components in Fig. 4 can also be attributed to this difference.

In conclusion, we have demonstrated a new, simple, and intense THz-radiation source just using bulk InAs. An average power of 650-μW was achieved in a 1.7-T magnetic field with 1.5-W excitation power, owing to the quadratic relationship to the magnetic field and excitation laser power, the high reflectivity of InAs, and smaller effective mass of the electron in InAs. A dramatic change of ellipticity was also observed for different magnetic fields. Further increase of magnetic field and excitation power will increase the THz radiation. Development of such simple and intense radiation sources will open up new applications of THz radiation.

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