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Significant enhancement of terahertz radiation from InSb by use of a compact fiber laser and an external magnetic field

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We investigated the magnetic-field dependence of terahertz (THz) radiation power from InSb. Significant enhancement of THz-radiation power is observed by using a compact fiber laser that delivered 100 fs optical pulses at a center wavelength of 1560 nm. Additionally, applying external magnetic fields dramatically enhanced the THz-radiation power. THz-radiation power reaches a maximum value at around 1.2 T, and its enhancement factor exceeds 100. From an applications viewpoint, this is a significant finding for practical light source design, since it is easily achieved by using a compact fiber laser and a conventional magnet. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1564290]

The generation and detection of terahertz (THz) radiation has been widely studied, due to its potential importance in a wide range of applications, including sensing or imaging and time-resolved spectroscopy in the far-infrared region. To facilitate such applied research, there is an urgent need to develop a compact emitter capable of producing intense, broadband radiation in the THz region. To date, various emitters for THz radiation have been demonstrated, including photoconductive switches,[1] semiconductor surfaces irradiated with ultrafast optical pulses,[2] two different color continuous wave lasers,[3] and parametric oscillators.[4] Among these techniques, using a semiconductor surface is a viable candidate for a practical light source, since it provides intense THz radiation without chemical processes or microfabrication techniques for emitter preparation.[5,6]

Since Zhang *et al.* reported the quadratic magnetic-field dependence of THz-radiation power from GaAs,[7] many studies have shown that application of a magnetic field causes an order of magnitude enhancement of THz radiation. This enhancement is explained by the change in the direction of carrier acceleration, which is induced by the Lorentz force in a magnetic field.[8–11] Previously, we significantly enhanced THz-radiation power by using InAs and reported quadratic magnetic-field and excitation intensity dependence of THz-radiation power.[12] Furthermore, we have observed anomalous magnetic-field dependence of THz-radiation power, including saturation, decrease, and recovery.[13] The saturation point found at around 3 T could lead to a practical compact THz-radiation source with a specially designed compact magnet.[14] For the enhancement of THz-radiation power, a smaller effective mass of photoexcited carriers is considered to be advantageous. Therefore, THz radiation from InSb is expected to be more intense than that from InAs, because InSb is a well known narrow-band gap semiconductor with a much smaller effective electron mass than that of InAs.[15,16] Howells, Herrera, and Schlie reported that the THz-radiation power from InSb is dramatically enhanced by using a 1900 nm laser as an excitation source.[17] However, they used an idler pulse of a Ti:sapphire-pumped optical parametric oscillator, which is a complex laser system. This becomes a critical obstacle in achieving a compact and practical THz-radiation source.

Here, we investigate the magnetic-field dependence of THz-radiation power from InSb by using a compact fiber laser that delivered 100 fs optical pulses with 160 mW at a center wavelength of 1560 nm. It is found that THz radiation from InSb is significantly enhanced by using a communication-wavelength laser as an excitation source, and its power is an order of magnitude greater than that of 780 nm optical excitation. Furthermore, applying an external magnetic field dramatically enhances THz-radiation power. THz-radiation power reaches a maximum at around 1.2 T, and its enhancement factor exceeds 100. The saturation point found at 1.2 T could lead to a practical THz-radiation source, since it is easily obtained by conventional magnets. This is the significant advantage of InSb over InAs in which the maximum power of THz radiation is obtained at around 3 T.

Figure 1 illustrates the experimental setup for the THz-radiation emitter in a magnetic field. A mode-locked fiber laser delivered 100 fs pulses at wavelengths of 780 and 1560 nm with a 50 MHz repetition rate (IMRA Model A50). The laser power was 160 mW at 1560 nm and 60 mW at 780 nm. The laser spot size on the sample surface was about 2 mm. The sample used was an undoped bulk InSb with a (100) surface. The conduction type was slightly n, and the carrier density was $4\times10^{14}\ \mathrm{cm}^{-3}$. A split-coil superconducting magnet with a cross-room-temperature bore can provide a

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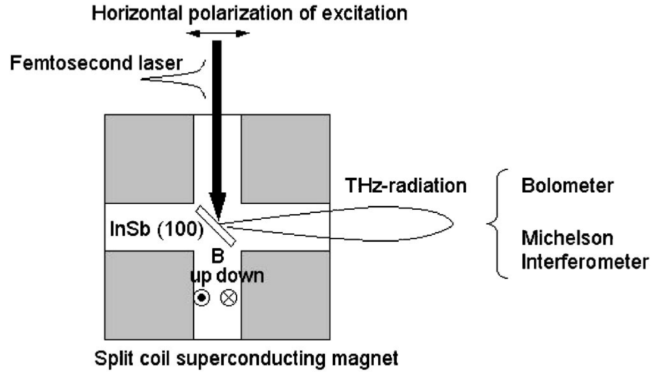

FIG. 1. Experimental setup for the THz-radiation emitter in a magnetic field. A mode-locked fiber laser delivered 100 fs pulses at wavelengths of 1560 and 780 nm with a 50 MHz repetition rate. The laser spot size on the sample surface was about 2 mm. The sample was undoped bulk InSb (100). A liquid-helium-cooled Ge bolometer was provided for detecting the power of the total radiation. A magnetic field was applied parallel to the sample surface. The maximum magnetic field of a split-coil superconducting magnet was 5 T.

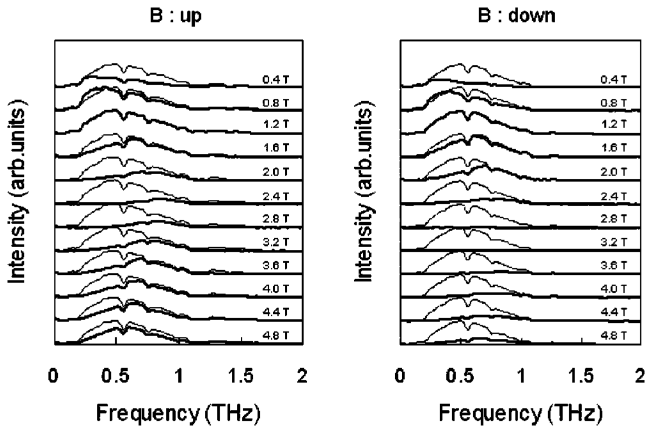

FIG. 3. Fourier spectrum of THz radiation from InSb at magnetic fields from 0.4 to 4.8 T. The InSb surface was irradiated with a femtosecond laser under excitation of 160 mW at a center wavelength of 1560 nm. The narrow line represents the THz-radiation spectrum measured at 1.2 T, which provides nearly the maximum radiation power.

magnetic field of up to 5 T. A liquid-helium-cooled Ge bolometer was provided for detecting the total radiation power. The advantage of using a bolometer for this measurement is the ease of capturing the beam, and the lack of timing or optical delay controls. The magnetic field was applied parallel to the sample surface and perpendicular to the incidence plane of the excitation laser. The Fourier spectrum of THz radiation was measured by a Michelson interferometer.

Figure 2 presents THz-radiation power measured in the presence of various magnetic fields. For a quantitative comparison, magnetic-field dependence of THz-radiation power from InAs (100) is also shown as reference data, since it is widely accepted that an InAs surface excited by a near-infrared laser provides intense THz radiation. Samples were irradiated with a femtosecond laser under excitation of 160 mW at 1560 nm and, 60 mW at 780 nm. At 1560 nm optical excitation, THz-radiation power exhibits quadratic dependence on the magnetic field, and increases until it saturates at around 1.0 or 1.2 T depending on the magnetic-field direction. THz-radiation power then decreases to a minimum value. As the magnetic field increases further, THz-radiation power recovers up to 5 T. We also observed a similar magnetic-field dependence for InAs.[13] Saturation and recovery in InSb occurred in a much lower magnetic field, as expected from the smaller effective mass of carriers in InSb compared to that of InAs. At 780 nm optical excitation, the magnetic-field dependence was very similar to that of the 1560 nm optical excitation case, except that its power is lower by an order of magnitude. Part of the drastic enhancement of THz-radiation power due to the excitation wavelength arises from increased number of carriers generated by the longer wavelength laser. However, this accounts for only a factor of 6 at most, comparing the average power and photon energy in both cases. Therefore, another effect should be considered to explain the enhancement of THz-radiation power. One possible explanation is the velocity overshoot. Under 780 nm optical excitation, photoexcited carriers gain high kinetic energy, and most of them are scattered into the *L* valley due to electron-phonon scattering. The effective electron mass in the *L* valley is much heavier than that of the Γ valley. This leads to the less efficient THz radiation. In contrast, at 1560 nm optical excitation, photoexcited carriers cannot gain sufficient energy to scatter into the *L* valley, and can contribute to generating THz radiation.

To explore the physical explanation of magnetic-field induced enhancement, we measured THz-radiation spectra with various magnetic fields using a Michelson interferometer. Figure 3 presents the THz-radiation spectrum measured at magnetic fields from 0.4 to 4.8 T. As the magnetic field increases from 0.4 to 1.2 T, lower-frequency components are drastically enhanced. As the magnetic field increases over 1.2 T, the spectrum becomes weaker and the lower-frequency components almost disappear. After reaching the minimum value, the intensity of the THz-radiation spectrum recovers, as observed in Fig. 2. The frequency bandwidth of the detection system is limited by the system response of Michelson interferometer and is estimated to be below 2 THz. Therfore, we could point out that the THz-radiation spectrum at a magnetic field of 1.2 T exhibits a broadband structure, that includes every frequency component observed in every magnetic field under 2 THz. The theoretical model, developed by

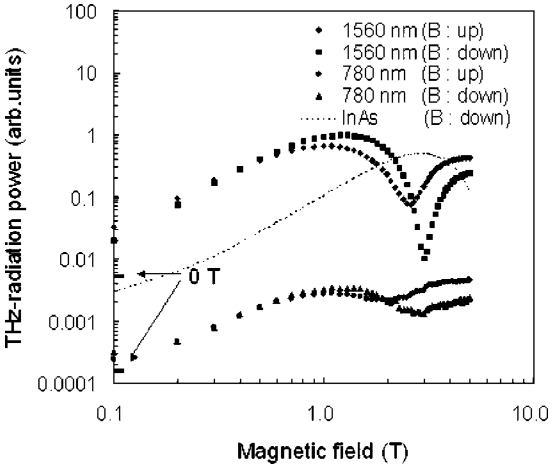

FIG. 2. Magnetic-field dependence of THz-radiation power. The InSb surface was irradiated with a femtosecond laser under excitations of 160 mW at 1560 nm and 60 mW at 780 nm. The dotted line represents the magnetic-field dependence of THz-radiation power from InAs (100) surface under excitation of 60 mW at 780 nm.

Johnston *et al.*,[8] demonstrates that a magnetic field enhances THz-radiation power by rotating the dipole with respect to the sample surface, and this enhances the THz radiation transmitted through the surface. Assuming that this model is valid, our results imply that applying a suitable magnetic field rotates the dipole to the direction, in which THz radiation is effectively extracted from the surface. In this case, the optimum magnetic field is considered to depend on the magnetic-field direction and incident angle of excitation pulses, since the acceleration direction of photoexcited carriers depends on both the direction of the Lorentz force and the initial diffusion. The diffusion process is initiated by the carrier-density gradient, and its direction is given by the incident angle of excitation pulses. The difference induced by the magnetic-field direction is also confirmed in Fig. 3. However, further investigation is required to discuss the detailed mechanism. For example, the incident-angle dependence of THz radiation power may provide clear results to validate the above model.

In summary, this letter has presented the magnetic-field dependence of THz-radiation power from InSb. At 1560 nm optical excitation, THz-radiation power from InSb is significantly enhanced by the external magnetic field, and its enhancement factor exceeds 100. The maximum radiation power is obtained at a magnetic field of 1.2 T, which is easily achieved by conventional magnets. There are two significant advantages of using InSb as the THz-radiation emitter rather than InAs. One is the capability to use an Er:fiber laser as an efficient excitation source, since more compact and high-average power fiber lasers should be available in the near future with the rapid progress of these lasers for optical communication.[18] The other is the low optimum magnetic field that can be easily achieved with slight modification, or by scaling down the previously designed 2 T magnetic circuit.[14] From these viewpoints, further research and improvement of InSb emitters should be continued together with InAs.

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