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Anomalous power and spectrum dependence of terahertz radiation from femtosecond-laser-irradiated indium arsenide in high magnetic fields up to 14 T

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We report on the terahertz radiation from femtosecond-laser-irradiated indium arsenide in high magnetic fields up to 14 T. It is found that the radiation power exhibits anomalous magnetic-field dependence, including saturation, decrease, and recovery up to 14 T. Moreover, the radiation spectrum possesses a clear periodic structure over 6 T.
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Numerous potential applications of terahertz (THz) radiation, including various imaging[1] and sensing[2] uses, have emerged with photoconductive antenna emitters.[3] However, severe sensitivity to alignment and insufficient power prevented the wide popularity of this device. To overcome these limitations, simple and intense THz-radiation sources have been studied eagerly.[4] Previously, we reported significant enhancement of THz-radiation power from femtosecond-laser irradiated indium arsenide (InAs) in a magnetic field by the quadratic dependence of the magnetic field and excitation power.[5] We found saturation of THz-radiation power in a magnetic field, around 3 T.[6] However, the mechanism of such anomalous magnetic-field dependence has still not been clarified.[7–11] The magnetic-field dependence in high magnetic fields will provide important information to explore such mechanisms, and to design more efficient and simple emitters for real-world applications. In this letter, we report that the THz-radiation power from femtosecond laser-irradiated InAs exhibits anomalous magnetic-field dependence, including saturation, decrease, and recovery up to 14 T. Moreover, the radiation spectrum possesses a clear periodic structure over 6 T, possibly due to the phase differences in radiation from different holes or due to the modulation of dielectric constant in high magnetic fields.

The experimental setup is illustrated in Fig. 1(a), including the excitation laser, magnet, emitter, and detection system. In previous experiments up to 5 T, a 25 mm diameter bore in a commercially available, split-pair superconducting magnet immersed in liquid helium was employed.[6] The large bore required in three orthogonal directions for the optical experiment obviously increased the heat flow to the cryostat. This heat flow limited the experimental time with the same optical alignment required for systematic measurements and restricted the practical magnetic field with the given spatial factor. To explore much higher magnetic field dependence, a cryocooled superconducting magnet with sufficient bore size should be prepared. For this purpose, a specially designed, cryocooled superconducting magnet with a 52 mm diameter room-temperature bore generates a magnetic field of up to 15 T.[12] An 82 MHz repetition rate mode-locked Ti:sapphire laser delivered approximately transform-limited 100 fs pulses at 800 nm. The excitation laser irradiated the sample at a 45° incidence angle. The sample was undoped bulk InAs with (100) surfaces.

A magnetic field was applied parallel to the sample surface and perpendicular to the incidence plane of the excita-

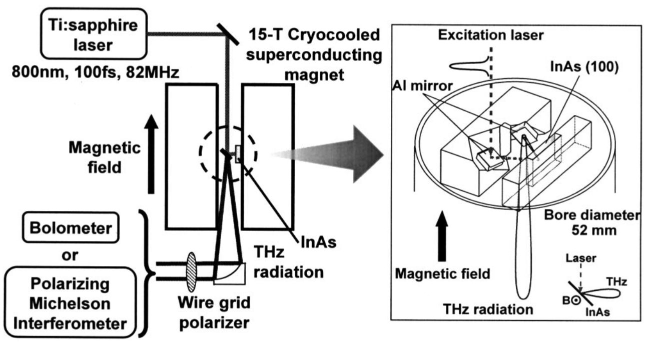

FIG. 1. Experimental setup for a THz-emitter module fitted to the 52 mm diameter bore of the superconducting magnet. The excitation laser and THz radiation should propagate parallel to the direction of the 2 m bore axis. The magnetic field was applied perpendicular to the laser incident direction and parallel to the InAs surface.

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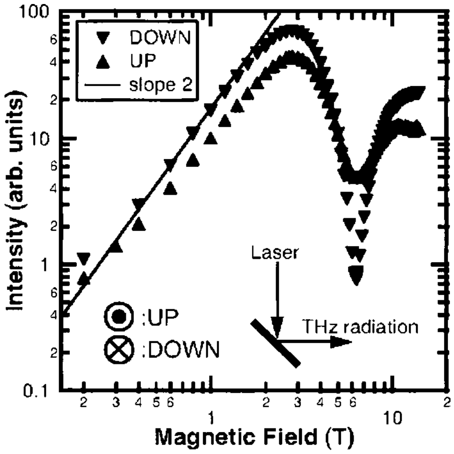

FIG. 2. The anomalous magnetic-field-direction dependent saturation, decrease, and recovery of THz-radiation power from InAs irradiated by a femtosecond-laser in a strong magnetic field. The radiation intensity has an asymmetric dependence on the magnetic field inversion, as observed in the low-field case. At around 6 T, the radiation intensity reaches a minimum value and recovers slowly.

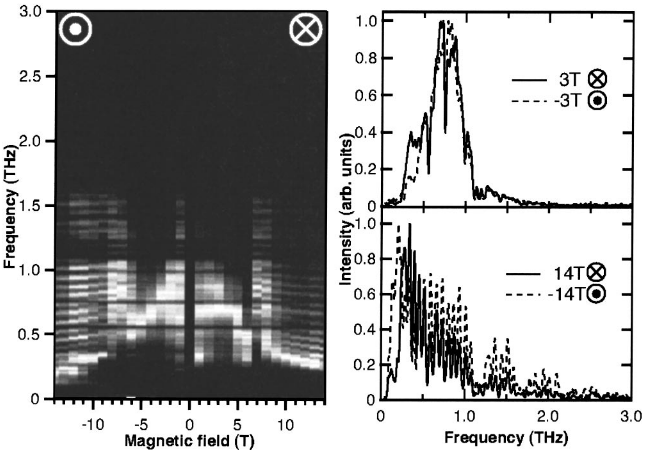

FIG. 3. The radiation spectrum exhibited an interesting magnetic dependence and periodic spectral structure. This might be attributed to the interference of the radiation from the different holes, since the radiation originating from different carriers should have had the same phase difference.

tion laser by a specially designed, compact mounting mechanism, as shown in Fig. 1(b). A liquid-helium-cooled bolometer was provided to monitor power. Anomalous magnetic-field-direction dependent saturation, decrease, and recovery of THz-radiation power from a femtosecond-laser irradiated InAs in a strong magnetic field was observed, as shown in Fig. 2. The radiation intensity demonstrated asymmetrical dependence on the magnetic field inversion, as observed in the low field case.[4] The maximum intensity was obtained at approximately 3 T. This can be achieved even with a permanent magnet incorporating a special design. The total radiation power is estimated as approximately 80 μW in average power from the InAs emitter.[13] From the viewpoint of applications, this was a significant finding for practical light source design.[14] The theoretical approach to understand the quadratic magnetic-field dependence is performed by Weiss *et al.*[15] The power enhancement factor η_p is written as

$$\eta_p \propto \left(\frac{e}{m^*}\right)^2 \tau^2 B^2 = aB^2, \tag{1}$$

where e, m^*, τ, B, and a are elementary electric charge, effective mass, scattering lifetime, magnetic field, and scaling factor, respectively. The magnetic field dependence of the radiation power shows good agreement with Eq. (1) for a magnetic field smaller than 3 T. Above 3 T, the linear approximation leading Eq. (1) is no longer valid because the magnetic field strength becomes very high. As Weiss expected in case of InSb, a deviation of quadratic dependence is clearly seen in case of InAs as shown in Fig. 2. There are many theoretical works to explain this saturation, however, no clear explanation has been proposed for decrease and recover.[7–11]

The THz-radiation spectrum was obtained by a polarizing Michelson interferometer. The radiation spectrum exhibited an interesting magnetic dependence and periodic spectral structure, as shown in Fig. 3. The cyclotron frequency was 3.36 THz for a 3 T magnetic field, therefore the spectral structure could not be explained by this process.[16] At around 6 T, the radiation intensity reached a minimum value and recovered slowly. This drastic change of the magnetic field dependence might be attributed to the change of the radiation mechanism in higher fields. There are two possible explanations for these experimental results.

One is a transient photocurrent originating from various carriers, such as electrons, light and heavy holes, and split-off holes.[17] The great difference in mass of these carriers (electron 0.027 m_0, light hole 0.024 m_0, heavy hole 0.41 m_0, and split-off hole 0.14 m_0) will result in a larger spatial separation of carriers by Lorentz force acceleration. That complicated screening effect originating from mass differences obviously adds further complexity to the system. Moreover, the initial velocity overshoot for the smaller mass electrons due to this acceleration occurred in lower magnetic fields, so that after reaching a quasisteady state, there should have been no acceleration for generating the radiation.[18] Therefore, the radiation from electrons should be dominant in lower magnetic fields, and the contribution from holes with a larger mass should play a major role in higher fields. Supporting this hypothesis, to some extent, the radiation spectrum exhibits a clear periodic structure over 6 T. This might be attributed to the interference of the radiation from the holes of different masses, since radiation originating from different carriers should have the same phase difference.

The other hypothesis is the change of dielectric constant originating from the existence of strong magnetic fields. According to the classical dynamics, dielectric constant depends on magnetic fields,[19] therefore, optical properties of semiconductor change dramatically in high magnetic fields. For example, the dielectric constant of InSb is well investigated in Ref. 19 and they reported that InSb becomes partially transparent in the THz region due to modulation of the dielectric constant in high magnetic field.[19] The same argument can be applied for InAs. If InAs becomes partially transparent in high magnetic fields, the radiation spectrum should exhibit a clear periodic structure as shown in Fig. 3.

In conclusion, we found that the THz-radiation power from femtosecond-laser irradiated InAs exhibited anomalous magnetic-field dependence, including saturation, decrease, and recovery up to 14 T. Moreover, the radiation spectrum possessed a clear periodic structure over 6 T, possibly due to the differently phased radiation from different holes or due to the modulation of the dielectric constant in high magnetic fields. These experimental findings imply there is rich, undiscovered physics to be explored. Moreover, this information should be helpful for the design of THz emitters for different applications.

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