Magnetic-field-enhanced generation of terahertz radiation in semiconductor surfaces

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(Received 11 July 2000; accepted for publication 30 October 2000)

A comparative study of magnetic-field-enhanced THz generation in semiconductor surfaces of InSb, InAs, InP, GaAs, and GaSb is reported. Applying an external magnetic field, the power of the generated THz radiation is increased for all examined semiconductor materials. The use of time-resolved measurements of the THz waveform allows to distinguish between the fraction of radiation originating from the surface depletion field and the fraction that is additionally generated by the magnetic field. It turns out that the power enhancement factor due to the magnetic field is inversely proportional to the effective electron mass. © 2000 American Institute of Physics.

The generation of THz radiation from semiconductor surfaces utilizing the surface depletion/enrichment field is a well established technique and has been examined previously. THz radiation emitted from semiconductor surfaces can be considerably enhanced applying an external magnetic field. This has been demonstrated for GaAs surfaces. Recently, the material InAs has been reported to be a source for high average-power THz radiation if an external magnetic field is present. Although average output power levels of up to several tens of μW have been obtained, the physical processes leading to the strong enhancement are not understood in detail for different semiconductor materials. Therefore, we have performed a systematic study of the power enhancement caused by an external magnetic field for five different semiconductor materials (InSb, InAs, InP, GaAs, GaSb). In particular, we distinguished between the fraction of THz radiation, which was generated by the magnetic field and the surface depletion/enrichment field, respectively. This was possible using time resolved measurements of the THz waveform.

In principle, the generation of THz radiation from semiconductor surfaces can be understood as follows: Pairs of free carriers are generated by a femtosecond IR pulse and experience different stages of transport processes. In a first stage, the created electron-hole pairs are polarized instantaneously.

In the second stage, the carriers are accelerated in the electric field originating in the surface depletion/enrichment layer of the semiconductor. The emitted electromagnetic field is proportional to the acceleration of the carriers. In the presence of an external magnetic field the carriers are additionally accelerated by the Lorentz force. If the surface depletion field \( E_D \) points along the \( z \) axis and the magnetic field \( B \) along the \( x \) axis (as shown in Fig. 1), the nonzero components of the time dependent acceleration are given by:

\[
a_z(t) = \frac{E_D}{B} \cdot \omega_c \cos(\omega_c t),
\]

where \( \omega_c = (eB/m^*) \) is the cyclotron frequency, \( m^* \) is the effective carrier mass, \( E_D \) and \( B \) are the surface depletion field strength and the magnetic field strength, respectively.

For small magnetic field strengths, \( \omega_c t \) is small, so that the trigonometric functions can be expanded and Eq. (1) becomes:

\[
E_y \approx a_y(t) \approx \frac{E_D}{B} \cdot \omega_c^2 t = \left( \frac{e}{m^*} \right)^2 E_D B t, \quad (2)
\]

\[
E_z \approx a_z(t) \approx \frac{E_D}{B} \cdot \omega_c = \frac{e}{m^*} E_D. \quad (3)
\]

The acceleration time \( t \) depends on the time until the carriers have reached a constant velocity and is limited by the carrier lifetime in the depletion/enrichment layer. There are two components of the acceleration generating two components of the electric field \( E_y \) and \( E_z \) of the THz pulse. Both components will add to the measured THz signal, which is polarized in the \( yz \) plane. The portion of the THz radiation corresponding to \( E_y \) only depends on the built-in electric field, while the component originating from \( E_z \) additionally depends on the magnetic field strength \( B \). In order to determine the contribution of the magnetic field to the generated THz radiation, the component \( E_y \) has to be measured.

FIG. 1. Orientation of the semiconductor samples with respect to the electric and magnetic fields.

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can be done using time resolved measurements of the waveform with and without magnetic field and extracting $E_y$ as will be shown below.

The experimental setup is shown in Fig. 2. The laser source is a mode locked Ti:sapphire laser with a repetition rate of 82 MHz and a pulse duration of 100 fs tuned to 800 nm. Behind the chopper an average power up to 500 mW is applied to the semiconductor emitters, which are used in reflective geometry. The (100)-oriented surfaces of all samples are polished for optical quality. The angle of incidence is 45° for all examined samples. It should be pointed out that the maximum THz power was obtained for an angle of incidence equal to Brewster’s angle. However, for experimental reasons the angle was kept fixed for all samples to 45°. The bulk samples are located between two permanent magnets providing a magnetic field perpendicular to the surface depletion field of the semiconductors. The strength of the magnetic field is varied by changing the separation of the two magnets. With a sample height of 2 mm a maximum magnetic field of 1.2 T is achieved in the center between the two magnets. The emitted THz radiation is detected with a 50 μm ion-implanted silicon-on-sapphire (SOS) dipole antenna (typically driven with an average IR power of 25 mW).

The magnetic part of the electric field component $E_y$ is determined in three steps: In a first step, the THz waveform is measured without an applied magnetic field. In this case, only $E_z$ will be responsible for the generated radiation (see Fig. 3 for InAs). In a second step, the magnetic field is applied and the waveform is measured for two opposite directions of the magnetic field keeping the field strength constant. These waveforms now contain both parts of the radiation, corresponding to $E_z$ and $E_y$, as shown in Fig. 4 for InAs. The third step is to subtract the waveform of Fig. 3 from the waveforms shown in Fig. 4. The result is displayed in Fig. 5. As expected from Eq. (2), the resulting waveform showing the component of the terahertz pulse generated by the magnetic field changes its phase by $\pi$ if the direction of the magnetic field is inverted.

With this method the materials contained in Table I were investigated. InP and GaAs are transparent for the THz radiation, therefore multiple reflections of the generated pulse occur at the surfaces of the sample and a pulse train is observed. In order to obtain a comparable value for the generated power, the measured waveform is squared and integrated with time. In this way, the reflected pulses from the rear surfaces are taken into account for InP and GaAs. In the third line Table I contains the THz power (in relative units) generated in the different materials without magnetic field. The THz power obtained with the different materials is given in relative units with respect to the power generated in InAs, which is by far the strongest source. For a magnetic field of 1 T, an increase of THz power can be observed in all materials investigated. Although InSb was found to have the largest increase in power compared to the pure surface depletion/enrichment field generation, the absolute maximum in THz power was still obtained for InAs.

For all samples, the dependence of the waveform on the magnetic field strength $B$ was recorded. The power of the magnetic field contribution is calculated and divided by the power measured without magnetic field. The resulting power enhancement factor $\eta_P$:

$$\eta_P \propto \frac{|E_y|^2}{|E_z|^2} = \left(\frac{e}{m^*}\right)^2 \tau^2 B^2 = a B^2$$

depends quadratically on the magnetic field strength $B$, where $\tau$ is an averaged acceleration time.
For all semiconductor materials, a quadratic dependence of the enhancement factor as a function of the magnetic field $B$ (see Fig. 6) is obtained as expected from Eq. (4). In the case of GaSb, the power of the THz radiation generated by the magnetic field is always less than the THz emission caused by surface depletion field ($\eta_{\text{p}} < 1$) up to the maximum field strength of 1 T for this measurement. The scaling factors $a$ of Eq. (4) is listed in Table I. Using the measured scaling factor and Eq. (4) an average acceleration time $\tau$ of the free carriers can be determined. Typical acceleration times for the semiconductor surfaces under investigation are between 500 fs and 1 ps. This value is in qualitative agreement with the pulse lengths of the generated THz pulses. For the indium containing compounds, a qualitative dependence of this scaling factor on the effective carrier mass ($m_{\text{InSb}}^* = 0.014 m_0$, $m_{\text{InAs}}^* = 0.027 m_0$, and $m_{\text{InP}}^* = 0.073 m_0$) is found being highest in the case of InSb, followed by InAs and InP. It is expected that the scaling factor $a$ increases with decreasing effective electron mass. For InSb, a deviation of the quadratic dependence can be seen for magnetic field strengths larger than 0.5 T. InSb has the lightest carriers and therefore the largest cyclotron frequency for a given field strength $B$. As a consequence, the linear approximation leading to Eqs. (2) and (3) is no longer valid at higher magnetic field strengths.

In summary, we have studied magnetic-field-enhanced THz generation from five different semiconductor surfaces. Using a simple Lorentz model for the acceleration of the carriers with a linear approximation, we have found that the power enhancement caused by the magnetic field is proportional to the square of the applied field for magnetic fields of up to 1 T. The scaling factor for the power enhancement is inversely proportional to the effective electron mass. The maximum power enhancement factor was obtained for InSb which has the smallest effective electron mass. Because of the small effective electron mass the power enhancement starts to saturate for InSb already at magnetic field strengths of only 0.5 T. The highest absolute power, however, was obtained under any conditions in InAs. This material produces considerably higher THz power even without magnetic field enhancement compared to the other semiconductors InSb, InP, GaSb, and GaAs and no sign of saturation was found for the power enhancement for magnetic fields of up to 1.2 T.


<table>
<thead>
<tr>
<th>Semiconductor material</th>
<th>InSb</th>
<th>InAs</th>
<th>InP</th>
<th>GaSb</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier concentration (cm$^{-3}$)</td>
<td>$1.4 \times 10^{14}$</td>
<td>$1.4 \times 10^{16}$</td>
<td>$1.0 \times 10^{15}$</td>
<td>$8.5 \times 10^{17}$</td>
<td>$1.0 \times 10^{18}$</td>
</tr>
<tr>
<td>THz power for $B=0$ T (r. u.)</td>
<td>0.7</td>
<td>100.0</td>
<td>8.2</td>
<td>0.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Power enhancement for $B=1$ T</td>
<td>26.1</td>
<td>8.8</td>
<td>3.7</td>
<td>0.7</td>
<td>11.1</td>
</tr>
<tr>
<td>Scaling factor $a$ (T$^{-2}$)</td>
<td>62.0</td>
<td>9.2</td>
<td>4.7</td>
<td>1.7</td>
<td>11.1</td>
</tr>
</tbody>
</table>

FIG. 6. Power enhancement factor plotted on a logarithmic scale as function of the magnetic field strength.