Terahertz Generation from High Index GaAs Planes at Different Angles of Incidence

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Generation of terahertz radiation from zinc-blende $\bar{4}3m$ crystal planes is presented. Comparison of theory with experimental measurements for high index (11*N*) GaAs crystals for normal and non-normal incidence of incoming radiation gives insight into different mechanisms involved in the generation of terahertz radiation from these crystals.

1. Introduction

Terahertz (THz) frequency radiation, ranging from 0.1-10 THz, can be obtained by excitation of ultra-short near-infrared (NIR) pulses on semiconductor materials. The generation of THz field without any external bias can be attributed to mechanisms such as transient current (TC) effects and optical rectification (OR) effects. The linear TC effect includes the surface-field (SF) effect which can be understood as acceleration of the charge carriers due to band bending by Fermi-level pinning near the semiconductor surface [1] and the Photo-Dember (PD) effect in which the dipole is generated due to different rates of diffusion of electrons and holes from the surface of the emitter crystal [2]. On the other hand, the nonlinear OR effect can be understood as difference frequency mixing of two or more frequency components. Since there are a number of frequency components present in the incident NIR beam, difference frequency mixing tends to generate the frequency in the range of THz radiation which can be either second order bulk OR effect [3] or higher-order surface-electric-field induced OR effect [4].

For some semiconductor crystals, THz radiation can be generated due to both TC and OR effects. Different experimental geometries can be employed in order to generate THz radiation from semiconductor crystals. In the case of transmission geometry [3], the incident NIR radiation is in the direction of the normal to the emitter crystal and THz field is detected in the straight-through direction. On the other hand in the case of reflection geometry [2], the NIR beam is incident at 45^{o} angle to the normal to the emitter crystal and generated THz radiation is detected in the specular-reflection direction. For TC emitters, the generated terahertz electric field is in the direction of the surface normal of the emitter crystal so the TC effect does not play any role in the THz generation in the transmission geometry. In the case of reflection geometry, in addition to the OR effect, transient currents can also play a role in THz generation due to a component of the surface field in the direction of detection.

The effect of rotation of the emitter crystal about its surface normal, known as the azimuthal angle dependence, can be helpful to distinguish between linear and nonlinear effects. The OR field tends to vary with the angular rotation of the emitter crystal, which is not the case for transient current emitters. In this paper, the generation of a THz field from high index (11*N*) GaAs crystals, where *N* ranges from 0 to 5, is presented for two orthogonal polarization components. The measurements are shown for GaAs *A* face (Ga-rich) and *B* face (As-rich) in both transmission and reflection geometries. By analysing these results we distinguish different crystallographic planes and obtain knowledge about the surface properties of the emitter crystal.

2. Theory for Optical Rectification

For an emitter exhibiting THz generation through both bulk and surface optical rectification, the THz field in the far field approximation can be given as [5]

$$\begin{bmatrix} E_p^{THz} \\ E_s^{THz} \end{bmatrix} = \begin{bmatrix} P_{y''}^{bulk} + P_{y''}^{surf} \\ P_{z''}^{bulk} + P_{z''}^{surf} \end{bmatrix} Z_0, \quad (1)$$

where $\hat{x}''$ is the direction of the surface normal, $\hat{y}''$ is the direction of the projection of the excitation beam onto the surface and $\hat{z}'' = \hat{x}'' \times \hat{y}''$. Z_0 is a proportionality factor which depends on experimental factors such as distance between emitter and detector. For the special case when the polarization angle for excitation radiation and the incident angle of excitation radiation with respect to the surface normal of emitter crystal are 0^o, the polarization components for bulk and surface OR in terms of azimuthal angle θ can be written as [5]:

$$\begin{bmatrix} P_{y''}^{bulk} \\ P_{z''}^{bulk} \end{bmatrix} = \frac{d_{14} E_0^2}{\sqrt{2}(N^2+2)^{\frac{3}{2}}} \begin{bmatrix} 3(N^2-1)\sin\theta - 3(N^2+1)\sin 3\theta \\ (N^2-1)\cos\theta - 3(N^2+1)\cos 3\theta \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} P_{y''}^{surf} \\ P_{z''}^{surf} \end{bmatrix} = -\frac{\gamma F_0 E_0^2}{2\sqrt{2}(N^2+2)^2} \begin{bmatrix} 3(N^2-1)\sin\theta + N(N^2+5)\sin 3\theta \\ N(N^2-1)\cos\theta + N(N^2+5)\cos 3\theta \end{bmatrix} \quad (3)$$

where d_{14} is second order susceptibility tensor component, E_0 is amplitude of electric field of incident NIR radiation, θ is the azimuthal angle, Miller indices $h = 1$, $k = 1$, $l = N$; γ is third order susceptibility tensor component and F_0 is amplitude of surface field of the GaAs emitter crystal.

It can be seen from Equations (2) and (3) that bulk and surface optical rectification components include terms $\sin\theta$, $\cos\theta$, $\sin 3\theta$ and $\cos 3\theta$. Thus, for semiconductor materials exhibiting THz field generation through these mechanisms, three cycle dependence for THz signal can be estimated as we rotate them about the surface normal.

3. Experimental Procedure and Results

Terahertz Time Domain Spectroscopy (THz-TDS) has been used to obtain the temporal behaviour of the terahertz field. THz is generated by ultrashort NIR pulses (<12 fs) with the centre wavelength of 790 nm. The GaAs crystal planes (110), (111), (112), (113), (114) and (115) with *A* and *B* faces have been investigated as THz emitters in both transmission and reflection geometry. Electro-optic detector (110) ZnTe has been used for detection of the THz field. The THz signal is measured as the differential voltage across the photodiode pair, generated due to rotation of the polarization in the ZnTe detector.

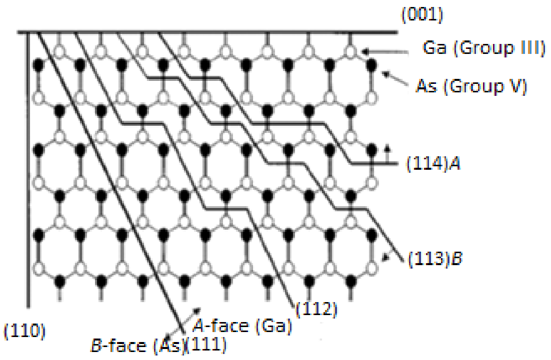

Fig. 1. Different crystal planes for GaAs (11*N*) with *A* (Ga-rich) and *B* (As-rich) faces.

The pump beam is horizontally (*p*) polarized. The components of the horizontal (*p*) and vertical (*s*) polarization of the generated THz field have been separated using a wire-grid polarizer. Azimuthal angle dependence has been obtained for all GaAs (11*N*) crystals by rotating them about the surface normal. Variation in the THz peak to peak (p-p) signal has been drawn against the azimuthal angle θ for both *p* and *s* polarizations. Fig. 1 represents different crystal planes for GaAs (11*N*) crystals with Ga-rich and As-rich faces.

3.1 Transmission geometry (0^o angle of incidence)

As discussed earlier, in this geometry the transient current effect does not play any role in the THz generation. So optical rectification is alone responsible for THz generation in this case, which is evident from the three maxima around the zero line for all emitter crystals as shown in Fig. 2. Here we have shown results for (112) and (114) crystal faces only. By comparing the results for (112) *B* and (114) *B* it can be seen that for (11*N*) crystals the overall THz signal is reduced as the value of the Miller index *N* increases.

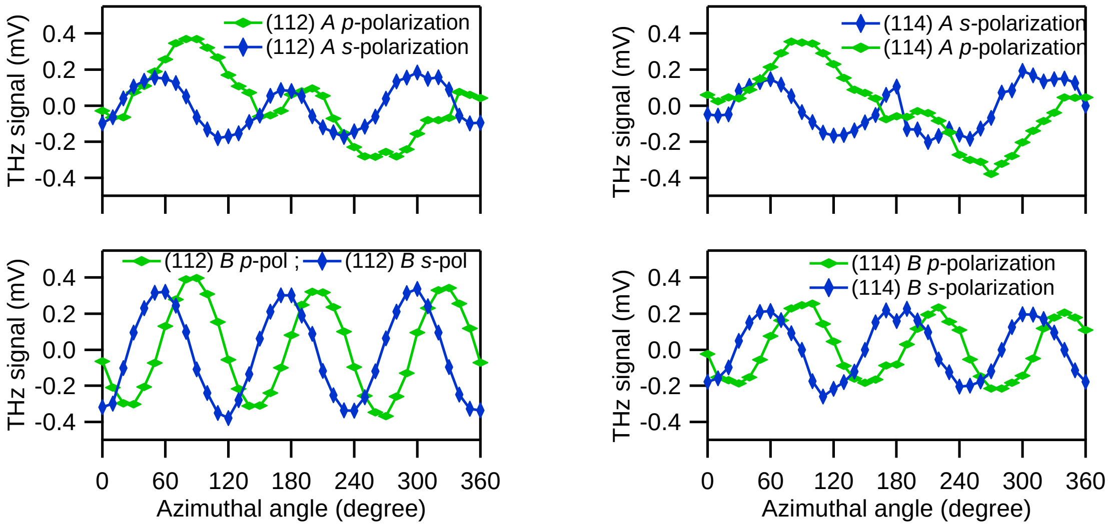

Fig. 2. Transmission geometry: Horizontal (*p*) and vertical (*s*) polarization components for GaAs (112) *A*, (112) *B*, (114) *A* and (114) *B* faces in transmission geometry. Each point represents the p-p THz signal measured at angle θ.

When the measured data is compared with the polarization components obtained from theory for optical rectification as given by equations (1), (2) and (3), it can be shown that both bulk and surface OR mechanisms are responsible for the generation of THz radiation from GaAs (111), (112), (113), (114) and (115) *A* and *B* faces in transmission geometry [5,6]. On the other hand, bulk OR is alone responsible for THz generation from (110) GaAs crystal planes (not shown here). Once we know the contribution of the bulk effect from (110) GaAs crystal, it can be used to calculate the surface field present on GaAs semiconductor surface by comparing experimental data with the theoretical curves for bulk and surface OR fields. The calculated surface field is the same on both Ga-rich and As-rich surfaces within experimental error [5].

3.2. Reflection geometry (45^o angle of incidence)

As shown in Fig. 3, in the case of reflection geometry, the THz is generated through the linear surface-field effect as well as nonlinear bulk and surface OR effects. Again only results for (112) and (114) crystal planes are shown here. The contribution from the linear effect is evident from the offset observed for horizontal polarized components for all crystal faces. This offset is around 1.6 mV for (112) faces and 0.6 mV for (114) faces. The nonlinear effects are again understood from the three cycle dependence (3θ dependence) of the generated THz signal for both polarization components. In the case of the *A* face, the surface field is in phase with the bulk field and hence the overall signal is enhanced for the *A* face. On the other hand, for the *B* face, the surface field is out of phase with the bulk field and hence the overall signal is reduced. These features are clearly visible from the *p*- and *s*- polarized components of the *A* and *B* faces as shown in Fig. 3.

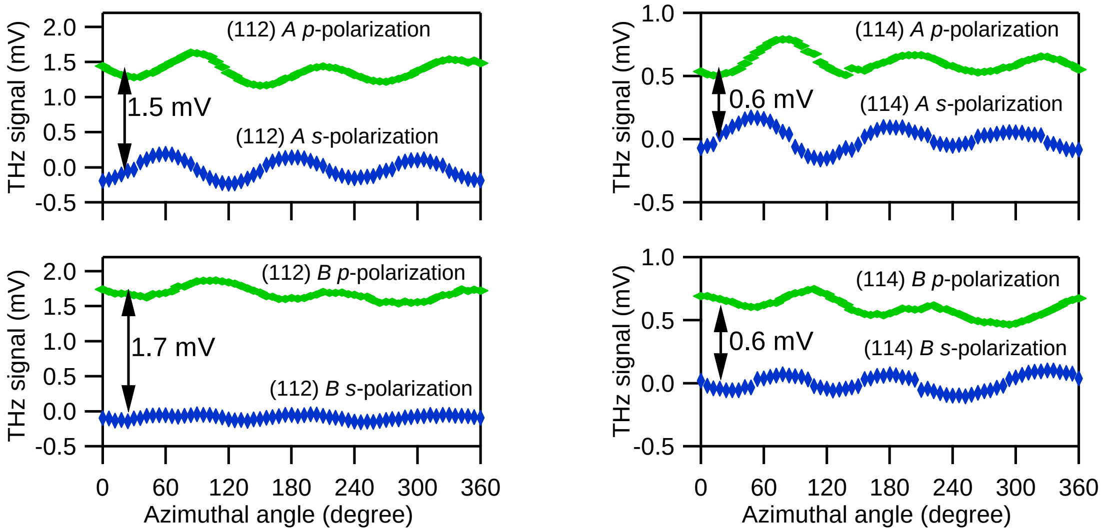

Fig. 3. Reflection geometry: Horizontal (*p*) and vertical (*s*) polarization components for GaAs (112) *A*, (112) *B*, (114) *A* and (114) *B* faces in reflection geometry. The effect of transient current has been represented in terms of an offset from the zero-line. The offsets are roughly 1.5 mV, 1.7 mV, 0.6 mV and 0.6 mV for (112) *A*, (112) *B*, (114) *A*, and (114) B respectively.

4. Conclusion

The azimuthal angle dependence has been measured for the THz signal emitted from GaAs (11*N*) samples for Ga-rich and As-rich faces. In the case of transmission geometry, the surface field can be calculated by using the bulk field which is deduced from (110) crystal planes. In the case of reflection geometry, it is possible to estimate the contribution of the transient current from the horizontally polarized components of the terahertz signal. It is also helpful to distinguish between the two faces of GaAs crystals. Such results can be obtained using high index crystal planes only. Alternatively, the optical rectification can be used to identify the crystallographic directions of the emitter crystal.

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