Terahertz emission mechanisms in InAs$_x$P$_{1-x}$

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The terahertz emission mechanisms from the surface of bulk InAs$_x$P$_{1-x}$ crystals have been examined. The dominant terahertz emission mechanism from InAs$_x$P$_{1-x}$ for low-fluence optical excitation is the photo-Dember effect for As compositions of 78% and greater while the surface field effect is dominant for As compositions of 50% and lower for the measured transport properties. The observed terahertz emission magnitude from the photo-Dember effect increased with As composition due to decreasing absorption depth. The observed terahertz emission magnitude from the surface field effect decreased with increasing As composition and was lower than modeled values due to the lower high-field mobility in the depletion region in those samples. © 2008 American Institute of Physics. [DOI: 10.1063/1.2827180]

Medical, security, and sensing/imaging industries stand to benefit greatly from the development of powerful terahertz sources. Terahertz radiation contains several orders of magnitude lower photon energy than x rays which would allow the medical industry safer, nonionizing alternatives to study the human body. Many illegal drugs, explosives, and biological warfare agents have characteristic absorption spectra in the terahertz range which would act as a fingerprint to identify not only the presence of harmful substances but also what that substance is to aid in hazard control for law enforcement and security systems. As many nonhazardous materials also have their own absorption spectra in the terahertz range, terahertz imaging could be used for nondestructive quality control.

Terahertz emission from semiconductor surfaces can arise from the photo-Dember effect, surface field effect, or from optical rectification. The surface field effect increases with increased carrier mobility and surface field strength (with ideal photoexcitation occurring only within the depletion region), while the photo-Dember effect increases for increasing electron temperature and carrier mobility ratio and decreasing absorption depth. The magnitude of terahertz emissions due to optical rectification changes with electro-optic coefficient and azimuthal angle compared to the incident laser pulse, and it has been found to yield a higher magnitude emission for incidence on the (110) planes as compared to the (100) planes of a zinc-blend semiconductor.

InP (Refs. 4 and 7–9) and InAs (Refs. 4 and 10–12) have proven to be very strong surface field and photo-Dember emitters respectively. A review$^{13}$ of band structure and electrical properties of InP and InAs indicates that the mixed alloy InAs$_x$P$_{1-x}$ could be an ideal candidate for terahertz emission. However, the exploration of terahertz emission from InAsP has not been possible due to difficulties in the growth of InAsP epitaxial layers. No lattice matched substrate exists onto which InAsP layers could be grown. This study has been made possible by bulk InAsP crystalline specimens synthesized from melt.

Terahertz measurements were performed using a standard terahertz-time domain spectroscopic system arrangement with a Ti:sapphire laser operating at a wavelength of 800 nm with a pulse width of 10 fs, a repetition rate of 80 MHz, and an excitation power of 400 mW. The laser was focused to a 0.5 mm focal spot diameter which yields a calculated fluence of 1 $\mu$J/cm$^2$. The ternary samples studied here had compositions in the range of 40%—85% As. The samples were unintentionally doped n-type material with mobility and carrier concentration, as shown in Fig. 1, obtained from dc Hall measurements performed at 300 K.

A separate photo-Dember and surface field model must be constructed as both mechanisms are expected to contribute to terahertz emission from InAsP. The surface field model$^{13}$ is dependent on the electron mobility, majority carrier concentration, photoexcited carrier concentration, absorption depth of the excitation pulse, and the width of the surface depletion region. The photoexcited carrier concentration is calculated using the focal spot area and the absorption

![FIG. 1. (Color online) Measured Hall transport properties of the InAs$_x$P$_{1-x}$ samples.](image-url)
depth of the material at the 800 nm excitation wavelength, which is 142 nm for InAs (Ref. 14) and 300 nm for InP.\textsuperscript{15} For interpolating the absorption depth in ternary InAs\textsubscript{1-x}P\textsubscript{x}, an equation similar to the band gap of the ternary compound as a function of composition was used with the same bowing parameter used for band gap calculation. The magnitude of band bending at the semiconductor surface is the difference between the pinned Fermi level at the semiconductor surface and the bulk Fermi level. The surface Fermi level is pinned at 0.49 eV above the valence band for ternary compositions with greater than 78\% As have their surface Fermi level pinned above the bulk Fermi level; therefore, these compositions will form an accumulation layer at the surface instead of a depletion layer and no surface field effect terahertz emission will result. Ternary depletion region width\textsuperscript{6} was determined using a linear extrapolation of the dielectric constant for ternary compositions. The modeled terahertz emission magnitude from the surface field effect, shown overlaid with the measured terahertz values in Fig. 3, accurately predicts a decreasing terahertz emission trend with increasing As composition between 40\% and 50\% As because the depletion region width is decreasing faster than the absorption depth for the measured carrier concentrations. The modeled values are higher (lower) than observed for the surface field (photo-Dember) effect. The discrepancies between measured and modeled values can be explained for each emission mechanism.

The photo-Dember effect relies on the ratio of the electron to hole mobility, the electron temperature, the high fields present at the surface of the samples (8.55 kV/cm for InP and 17–20 kV/cm for 40\%–50\% As compositions) will significantly reduce the effective mobility of the carriers in the depletion region\textsuperscript{6} due to hot carrier effects. This reduction of effective mobility is not accounted for in the model of Ascazubi \textit{et al.}\textsuperscript{6} and must be taken into consideration. The InP field magnitude is very close to the point of zero effective mobility and an effective mobility value equal to \~20\% of the measured low field mobility will match with the observed terahertz emission value. The 40\%–50\% As composition will maintain their mobility for larger fields than InP using a linear interpolation of the field dependence from the binaries,\textsuperscript{19,20} and an effective mobility equal to 50\% of the low field mobility provides a match to the observed terahertz values. These effective mobility values are reflected in the modeled values in Fig. 4.

The photo-Dember model becomes less sensitive to variations in electron mobility, and the high fields present at the surface of the samples (8.55 kV/cm for InP and 17–20 kV/cm for 40\%–50\% As compositions) will significantly reduce the effective velocity of the electrons. For the 78\%–85\% As composition samples, by increasing the Hall mobility by a factor of 2, an order of magnitude reduction in bulk carrier concentration and an increase in the estimated hole mobility by (for ternary compositions a linear interpolation can be used). The calculated photo-Dember model values for the samples show (in Fig. 3) that the photo-Dember effect is the dominant emission mechanism for As compositions of 78\% and greater. Terahertz emission from the photo-Dember effect increases with As composition due primarily to the decreasing absorption depth, which increases photoexcited carrier concentration and increasing photoexcited electron temperature.

The surface field effect model is linearly dependent on electron mobility, and the high fields present at the surface of the samples (8.55 kV/cm for InP and 17–20 kV/cm for 40\%–50\% As compositions) will significantly reduce the effective mobility of the carriers in the depletion region\textsuperscript{6} due to hot carrier effects. This reduction of effective mobility is not accounted for in the model of Ascazubi \textit{et al.}\textsuperscript{6} and must be taken into consideration. The InP field magnitude is very close to the point of zero effective mobility and an effective mobility value equal to \~20\% of the measured low field mobility will match with the observed terahertz emission value. The 40\%–50\% As composition will maintain their mobility for larger fields than InP using a linear interpolation of the field dependence from the binaries,\textsuperscript{19,20} and an effective mobility equal to 50\% of the low field mobility provides a match to the observed terahertz values. These effective mobility values are reflected in the modeled values in Fig. 4.

The photo-Dember model becomes less sensitive to variations in electron to hole mobility ratio for ratios greater than 10 and for preexcited carrier concentrations significantly less than the photoexcited carrier concentration (both of which are true for the 78\%–85\% As samples). A close examination of the model of Ascazubi \textit{et al.}\textsuperscript{6} shows a linear dependence on increasing hole mobility for mobility ratios greater than 10. Further examination of this phenomenon is necessary, but may be due to the increase in motion of the center of charge which forms the diffusion current due to the increased velocity of the holes compared to the significantly greater velocity of the electrons. For the 78\%–85\% As composition samples, by increasing the Hall mobility by a factor of 2, an order of magnitude reduction in bulk carrier concentration and an increase in the estimated hole mobility by
an 800 nm excitation pulse wavelength. We discovered that for samples with 40%–50% As, the emission is surface field effect dominant and is quite sensitive to mobility fluctuations from high surface fields. We also discovered that the photo-Dember effect is the dominant mechanism for As compositions of 78%–85% and that terahertz emissions from these samples are very sensitive to hole mobility, absorption depth, and electron temperature. The general trend across the ternary shows an increase in the terahertz emission magnitude for increasing As composition. However, the local trend between 40% and 50% As shows a decrease in the terahertz emission intensity with increasing As composition. This is attributed to the decrease in the dominant surface field effect due to a diminishing surface potential between the surface and bulk Fermi levels.

FIG. 4. (Color online) (a) The fitted terahertz model accounting for estimated reduction in effective mobility due to electron velocity saturation in high surface fields and estimated transport characteristic variation across the sample surface. (b) The composite fitted model values overlaid with the measured values. The surface field and photo-Dember models add as the emitted pulse peaks have the same sign.

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30 cm$^2$/V s would allow a good agreement between the modeled and measured values, as shown in Fig. 4. This clearly demonstrates that microscopic variations in transport properties in alloy semiconductors such as InAsP can affect the terahertz emission strength. Variations in transport properties as quoted above have been experimentally measured in selected samples during our studies. With improvements in material growth technologies, such variations are expected to be eliminated and a better agreement between theoretically predicted and experimentally measured terahertz properties will be seen.

In summary, we have observed strong terahertz emission from InAs$_x$P$_{1-x}$ over a wide range of alloy composition for