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Title: Time Domain Spectroscopy of the Magnetic Field Induced Metal-Insulator Transition in n:InSb

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Time Domain Terahertz Spectroscopy of the Magnetic Field Induced Metal-Insulator Transition in n:InSb

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Abstract. Temperature (T) and frequency (ω) dependent conductivity measurements are reported for n-type indium antimonide (InSb) around the magnetic field induced metal-insulator transition (MIT). For the sample with electron density n= 2.15×10^{14} cm^{-3}, the critical field is observed at ~0.7 T in dc transport measurements. The frequency dependent conductivity $\sigma(\omega)$ measured via terahertz time domain spectroscopy indicates a higher critical field ~1.2 T. Both $\sigma_{dc}(T)$ and $\sigma_1(\omega)$ at low temperatures show power law dependence with exponents of α=1.2.

It is well known that n-type indium antimonide (InSb) with a very low carrier concentration (~10^{14} cm^{-3}) undergoes a magnetic field induced MIT[1]. Although dc transport measurements in magnetic field suggest the existence of a field-induced MIT in InSb, the dynamics of the transition remain largely unexplored. To understand the dynamics of the field induced MIT in semiconductors in detail, frequency dependent measurements are necessary in the terahertz (THz) range. We performed high frequency (100 GHz ~ 1.5 THz) time domain spectroscopy on InSb under high magnetic fields.

For the purpose of these THz measurements, we employ a method[2] for THz time-domain spectroscopy directly in the cryogenic bore of high field magnets. Miniature, fiber-coupled THz emitters and receivers are constructed for working down to 1.5 K and up to 17 T. Under applied magnetic fields, we measured both the temperature dependent dc conductivity by conventional transport methods and the frequency dependent complex conductivity by time-domain spectroscopy. For the dc conductivity measurements, a sample with Hall bar configuration was measured in a Quantum Design physical properties measurement system (PPMS). The Hall measurement shows that the carrier concentration is 2.15×10^{14} cm^{-3} at 2 K near zero magnetic field.

For MIT in three dimensions (3D), it is established that the temperature dependence of the conductivity usually follows the power law[3]

$$\sigma_{dc}(T) = AT^{\alpha} + C, \qquad (1)$$

across the transition point, with $C>0$ for the metallic state and $C<0$ for the insulating state. The critical point of the transition corresponds to parameter C equal zero.

Scaling arguments can be used to describe the frequency dependence of the real conductivity at low temperature[4]. At low temperatures ($T\rightarrow0$) and at fields close to the critical field, the conductivity should follow the power law

$$\sigma_1(\omega) = A'\omega^{\alpha} + C', \qquad (2)$$

also with a positive value of C' appropriate for the metallic state and a negative value of C' for the insulating state.

Figure 1 shows dc conductivity from 2 K to 12 K while varying the magnetic field from 0.3 T to 1.0 T in 0.1 T steps. Fitting the $\sigma_{dc}(T)$ data in different fields to Eq. (1), we found that α=1.2 best describes the data over all the temperature range in contrast to α=0.5 for the density tuned MIT in NbSi[5]. The temperature dependent dc conductivity clearly follows equation (1). The critical field, at which C=0, is found to be 0.7 T

Using the fiber coupled THz antennas, time-domain THz measurements were performed in magnetic fields in the Faraday geometry. Complex transmission can be obtained by Fourier transform of detected time-domain THz signal. From the complex transmission of THz pulses and reference THz pulses, we calculate the complex dielectric constant of InSb by iteratively solving Eq. (3) below[6].

$$\sqrt{\varepsilon(\omega)}-1=\frac{c}{i\omega d}\ln\left(\frac{E_t(\omega)}{E_0(\omega)}\frac{(1+n)^2}{4n}\right), \quad (3)$$

where $E_0(\omega)$,$E_t(\omega)$ are the incident and transmitted THz fields, ε is the complex dielectric constant, n is the complex index, d is the sample thickness, and c is the speed of light. Complex conductivity can then be easily obtained from the complex dielectric constant.

$$\sigma(\omega)=i\varepsilon_0\omega\left(\varepsilon(\omega)-1\right), \quad (4)$$

where ε_0 is permittivity of free space.

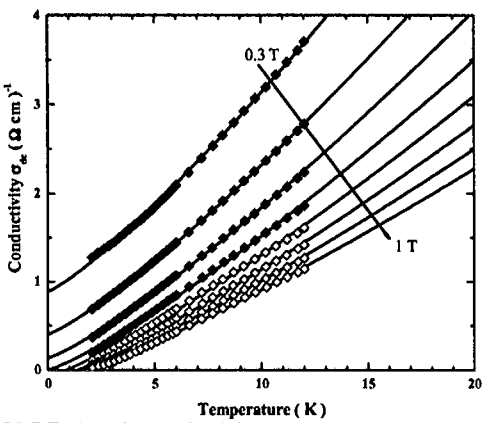

FIGURE 1. dc conductivity versus temperature as the magnetic field changes from 0.3 T to 1.0 T (from top to bottom). The critical field is observed around 0.7 T. The lines are fitted curves to Eq. (1) with α=1.2.

The frequency dependent real conductivity ($\sigma_1(\omega)$) is plotted in Fig. 2 with fits to Eq. (2). We only fit data in the frequency range $\hbar\omega \gtrsim 3.5kT$, such that the quantum limit is satisfied, and we can also extract the dynamic exponent from $\sigma_1(\omega)$. The lines in Fig. 2 are power law fits to Eq. (2) with α=1.2, the same exponent from DC transport measurements. We see that α=1.2 also describes $\sigma_1(\omega)$ at T=2 K. These data suggests a critical point of 1.2 T where $\sigma_1(\omega)$ intercepts the origin.

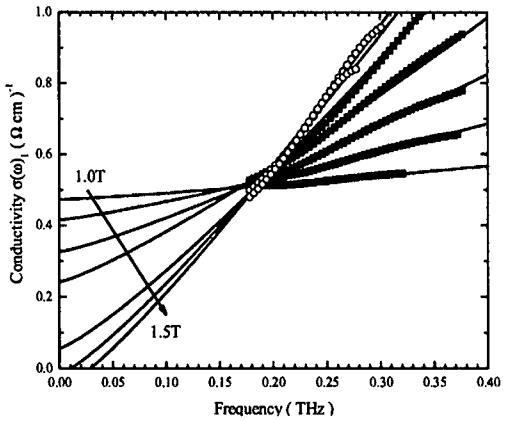

FIGURE 2. Real conductivity $\sigma_1(\omega)$ versus frequency as the magnetic field changes from 1.0 T to 1.5 T (from top to bottom) at T= 2 K. The lines are fitted curves to Eq. (2) with α=1.2.

In conclusion, we have studied the magnetic field induced MIT in InSb (n = 2.15×10^{14} cm^{-3}) by both temperature dependent dc conductivity and frequency dependent conductivity. Both $\sigma_{dc}(T)$ and $\sigma_1(\omega)$ can be fit by a power law dependence with exponents of α=1.2. However the temperature dependent dc conductivity gives a critical field ~0.7 T and the frequency dependent conductivity gives ~1.2 T.

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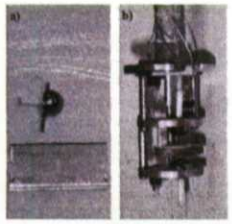
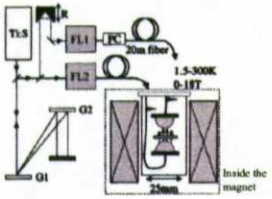
Experimental setup: THz spectroscopy in high magnetic fields



Fiber-coupled THz antennas



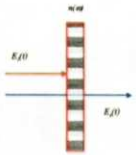
Experimental Setup

Ti:S	Ti:sapphire pulsed laser
FL1, FL2	fiber launchers
G1, G2	gratings
PC	polarization controller
R	scanning retro-reflector

S. A. Crooker, *Rev. Sci. Instrum.* **73**, 3258 (2002).

Time-domain terahertz spectroscopy

Calculation of complex conductivity



Complex dielectric constant calculation

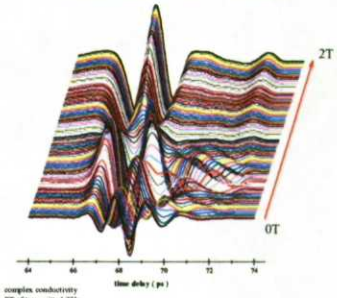
$$\sqrt{\tilde{n}(\omega)}-1=\frac{c}{i\omega d}\ln\left(\frac{E_s(\omega)}{E_r(\omega)}\frac{(1+\tilde{n})^2}{4\tilde{n}}\right)$$

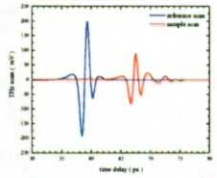
Complex conductivity

$$\sigma(\omega)=i\varepsilon_0\omega\left(\varepsilon(\omega)-1\right)$$

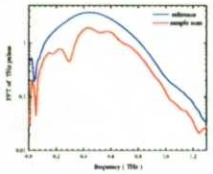
$\tilde{n}(\omega)$: complex conductivity
$E_s(\omega)$: FT of transmitted THz
$E_r(\omega)$: FT of incident THz
$\tilde{n}(\omega)$: complex index of refraction
ε_0 : permittivity of free space

Field dependent time scan of THz pulses

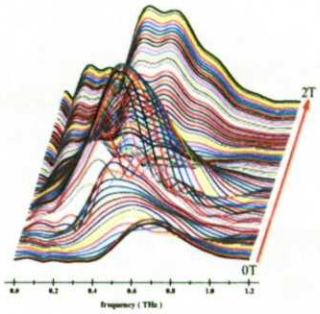




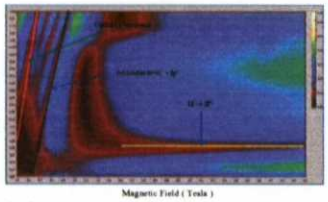
Fourier Transform of THz pulses



Fourier transform of transmitted THz pulses

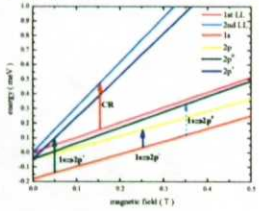


Transmission of THz pulse through n-type InSb

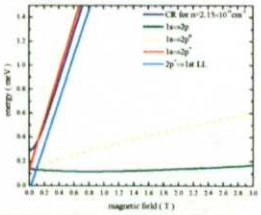


- Cyclotron resonance and plasma edge is observed in low magnetic fields.
- (1st Landau level) → $2p^+$ transition is observed from ~0.3 T.
- ($1\rightarrow 2p^-$) transition exists up to high magnetic fields, but disappears in high temperature. (> 10K).
- Large absorption near the metal-insulator transition field is observed. (possibly due to weakening of the selection rule.)

Impurity and Landau levels of InSb



Possible level transitions in InSb



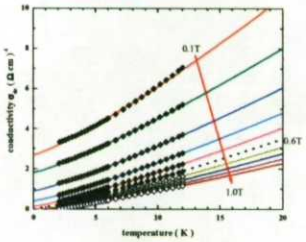
Temperature dependent dc conductivity

$\sigma_{dc}(T) = AT^{\alpha}+C$

$C > 0$ *metallic region*
$C = 0$ *transition region*
$C < 0$ *insulating region*

temperature dependent dc conductivity can be fit using α=1.2.

Critical Field is ~0.7 T.



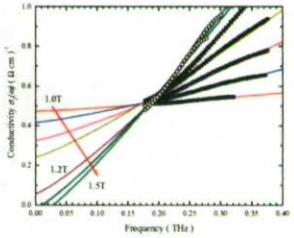
Frequency dependent conductivity

$\sigma_1(\omega) = A\omega^{\alpha}+C$

$C > 0$ *metallic region*
$C = 0$ *transition region*
$C < 0$ *insulating region*

frequency dependent $\sigma_1(\omega)$ conductivity can Also be fit with α=1.2.

Critical Field is ~1.2 T.



Conclusions

- Time-Domain terahertz spectroscopy is performed on n-type InSb (n = 2.15×10^{14} cm^{-3}) semiconductor in the magnetic fields and the complex conductivity is calculated.
- Cyclotron resonance, ($1\rightarrow 2p^-$) and (1st Landau level → $2p^+$) transitions are observed.
- Both the temperature dependent dc conductivity and the frequency dependent real conductivity can be fit with power laws ($\sigma_{dc}(T) = AT^{\alpha}+C$ and $\sigma_1(\omega)=A'\omega^{\alpha}+C'$) near the metal-insulator transitions.
- Power law fit has a common exponent of α=1.2. Critical field is found to be B_c~0.7 T from the temperature-dependent dc conductivity, and B_c ~1.2 T from the frequency-dependent THz conductivity.

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