Exploring the Effective Mass of Semiconductors Using Infrared Faraday Rotation

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Abstract

Due to the influence of the crystal in which an electron inhabits, its mass can effectively take on different values. By measuring the effective mass of an electron inside a crystal, therefore, one can gain a deeper understanding of the dynamics related to electron transport that is vital for designing devices. In this experiment, we have used a spectroscopic technique, based on Faraday Rotation, to determine the effective masses of several semiconductors. In this technique, as linearly polarized light passes through a material, the plane of polarization changes due to the presence of the magnetic field. By measuring the angle of rotation, one can recover the effective mass of the material provided that its index of refraction is known. We incorporated a few fairly strong permanent magnets (~0.5 Tesla) into a spectroscopic ellipsometer and obtained polarized-dependent transmission spectra from 2 to 33 μm (300 cm^{-1} to 5000 cm^{-1}) for both forward and reversed magnetic field plus for different bias angles. By plotting the rotation as a function of wavelength-squared, the effective masses of the samples were determined. In a separate spectroscopic measurement, we obtained the dispersion of the index of refraction of the material, which was used to calculate its effective mass. In this project, the effective masses of two InP samples (with different carrier concentrations) and an n-type GaAs sample were found using this technique.

Theory

The Faraday effect is an interaction between electromagnetic waves and magnetic field inside a material. When linearly polarized light passes through a material, placed inside a magnetic field, the plane of polarization will rotate depending on the electric properties of materials plus field strength along the direction of light propagation.

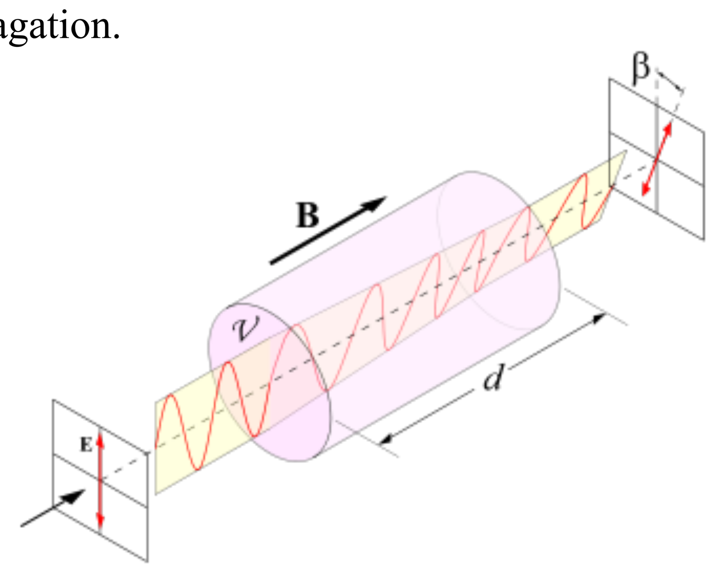


Fig. 1. Faraday Rotation

This effect is due to left and right circularly polarized waves propagating at slightly different speeds in a material. A linearly polarized wave can be constructed via superposition of right and left circularly polarized waves of equal amplitude. When a linearly polarized light passes through a medium, free electrons in the medium have slightly different responses to right and left circularly polarized components in the presence of magnetic field. This results in different dielectric constants for the two circularly polarized waves, and hence creates a phase difference between the two waves. The result of such phase difference is the rotation of plane of polarization.[1]

For semiconductor samples, the angle of Faraday rotation due to free electrons is given as follows (in MKS units)[1]:

$$\theta = \frac{Ne^3 BL}{8\pi^2 c^3 \varepsilon_0 n m^{*2}} \lambda^2 \qquad \text{[Eqn. 1]}$$

where N is the carrier concentration, L is the thickness, ε_0 is the permittivity of free space, n is the refractive index, and m^* is the effective mass. The equation reveals that Faraday rotation angle is linearly dependent on wavelength-squared. Therefore the electron effective mass can be determined once the Faraday rotations and corresponding incident wavelengths are measured.

Experimental Details

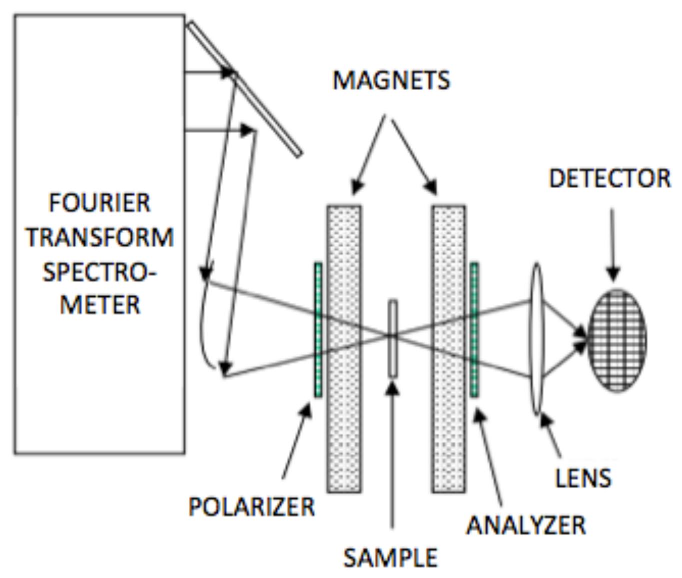


Fig. 2. Schematic of Experimental Set-up[2]

Fig. 2 shows the schematic of general experimental set-up. The magnetic field is aligned in a way such that it is in parallel with the direction of incident light. The actual set-up was constructed by incorporating a plastic sample holder and 2 strong permanent magnets (combined field 4630±50 gauss) into the in-house IR-Spectroscopic Ellipsometer. The set-up is shown in Fig. 3 and Fig. 4 below.

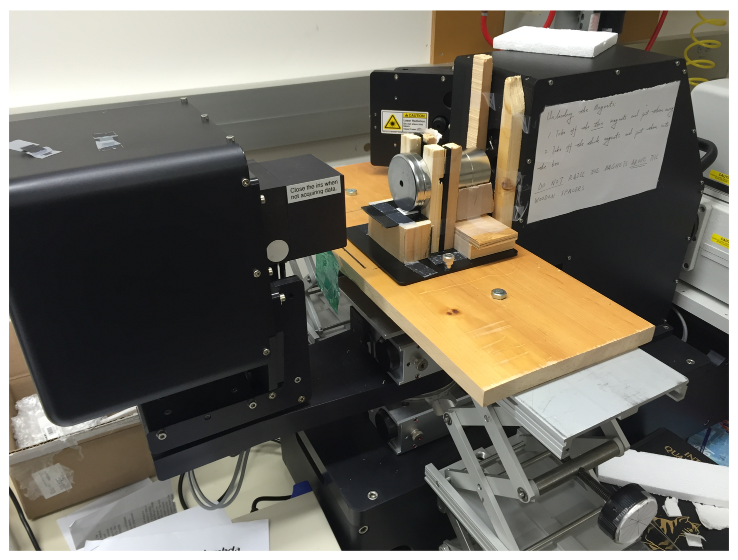


Fig. 3. Experimental Set-up

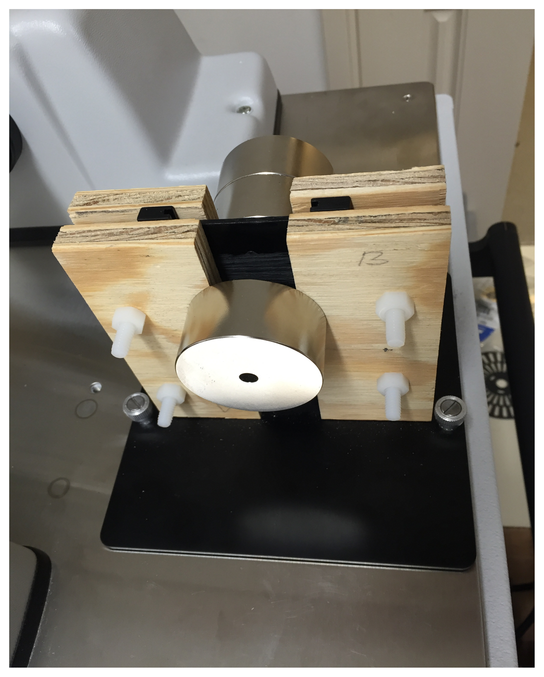


Fig. 4. Sample Holder and Magnets (Close-up)

The experimental data were taken in the following procedures:

1. Place the magnets such that the magnetic field points in the direction of incident light propagation; obtain transmission spectra of the sample for 30° and 45° bias angles (between polarizer and analyzer).
2. Reverse the direction of the magnetic filed and take the transmission spectra for the same bias angles.
3. Take an ellipsometry spectrum to obtain the dispersion of the index of refraction n of the sample.

The spectra are taken for two opposite magnetic fields in order to increase the sensitivity to the rotation change in the experiments.

The conversion of transmission spectra into Faraday rotation spectra is given by the following equation:

$$\theta = \tan^{-1}\left(\frac{1-\sqrt{r}}{1+\sqrt{r}}\cot\alpha\right) \qquad \text{[Eqn. 2]}$$

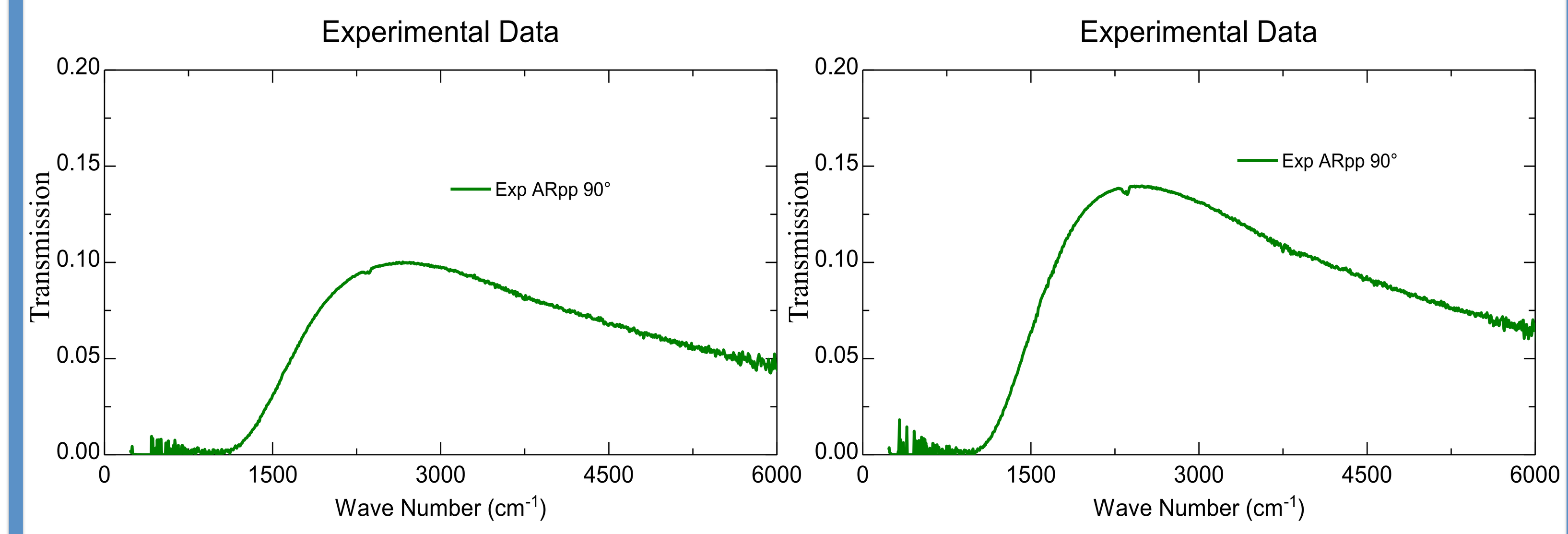
where α is the bias angle, and r is the ratio between normalized intensities of transmitted light in forward and reversed magnetic field. Then given Eqn. 1, we can plot $n\theta$ as a function of λ^2, from which the effective mass can be calculated.

References

[1] Moss, T. S.; Burrell, Geoffrey J.; Ellis, Brian. *Semiconductor Opto-Electronics*. London: Butterworths, 1973.
[2] Clarke, Frederick W. “Faraday Rotation Analysis of Narrow Gap Semiconductors: An Optical Alternative to the Hall Test.” Vilnius Gediminas Technical University Semiconductor Physics Institute, 2006. Web.
[3] Cardona, Manuel. “Electron Effective Masses of InAs and GaAs as a Function of Temperature and Doping.” *Physical Review*, Vol. 121, No.3 (1961).
[4] Kittel, Charles. *Introduction to Solid State Physics (7th Edition)*. New York: John Wiley & Sons, Inc., 1996.

Results & Discussion

The data and subsequent analyses were performed for two InP samples (with different carrier concentrations) and an n-type GaAs sample. The experimental graphs of only n-type GaAs for 45° bias angle are shown below as examples.



(a) Forward B Field (b) Reversed B Field

Fig. 5. Transmission Spectra of N-Type GaAs for 45° Bias Angle

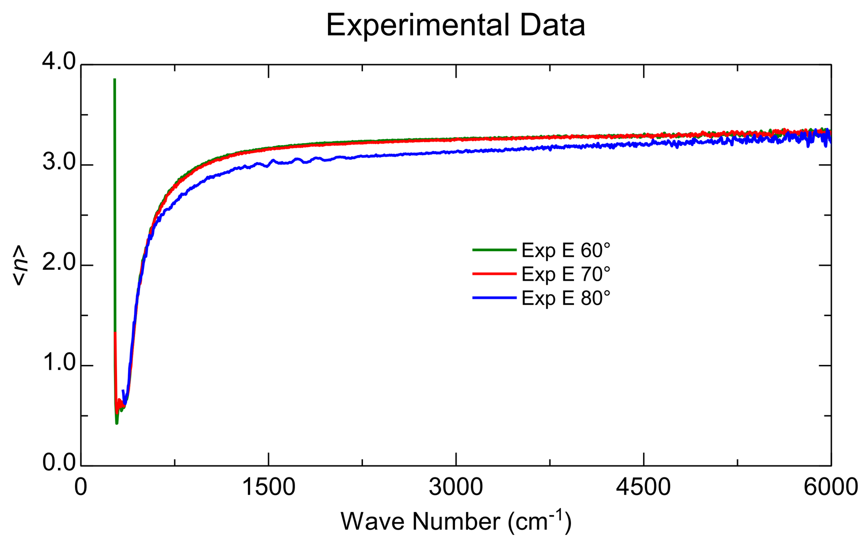


Fig. 6. Ellipsometry Spectrum (index of refraction) of N-Type GaAs

The ellipsometry spectrum was taken for three different incident angles (60°, 70°, and 80°) to obtain the dispersion of the index of refraction plus the standard errors of the dispersion. Since other constants in Eqn. 1 are non-dispersive, we can safely plot $n\theta$ as a function of λ^2 to obtain the linear relation. The plot was made in Origin 9.8 and is shown in Fig. 7 below.

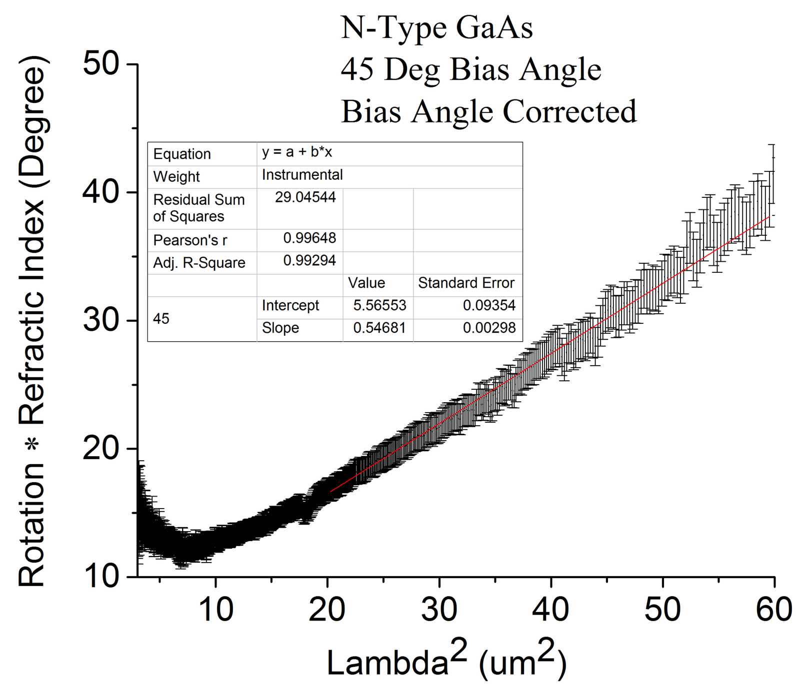


Fig. 7. Faraday Rotation Spectrum of N-Type GaAs for 45° Bias Angle

The function is only fitted for linear region of the plot. At lower wavelengths, the linear model does not fit the experimental plot since the energy is relatively close to band gap. The effective mass can be obtained from the slope of the fit as long as other constants (carrier concentration and thickness) are measured. The calculated results for all three samples are listed in Table 1 below.

Sample	Carrier Concentration (cm^{-3})	Thickness (mm)	Effective Mass 30° bias angle	Effective Mass 45° bias angle
GaAs (n)	(1.3±0.1)×10^{18}	0.45±0.02	(0.089±0.004)m_0	(0.086±0.004)m_0
InP	(1.9±0.1)×10^{17}	0.37±0.01	(0.089±0.003)m_0	(0.089±0.003)m_0
InP	(2.8±0.1)×10^{18}	0.36±0.01	(0.105±0.002)m_0	(0.102±0.002)m_0

Table 1. Measured Constants and Experimental Results

The values are within the same order of magnitude as the results found in literatures[3]. Also the results of different bias angles are consistent within one standard deviation. The results have demonstrated that IR Faraday rotation technique proves to be a fairly reliable method of determining the carrier effective mass of low band gap semiconductors.