Temperature Dependence of Near-Infrared Absorption in InN Grown on Si by Molecular Beam Epitaxy

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Indium Nitride (InN) is a semiconductor with a very small bandgap, thus making it a promising material for high speed electronics and in solar cells. Infrared absorption of RF-MBE-grown InN layer on Si substrate was measured using a photovoltaic InAs detector at 4 to 300 K. The infrared light source used was a halogen lamp. Bandgap for the samples is estimated to be 0.64 eV for wurtzite structure at 300 K. A pronounced peak at 0.55 eV region is speculated to be caused by transition from the InN conduction band to Si conduction band. The asymmetrical line shape of this peak could be attributed to the quantum interference between the conduction bands of Si and InN.

1. **Introduction**:

Indium Nitride (InN) is a narrow bandgap semiconductor material with high electron mobility, light effective mass and very high carrier saturation velocity making it a promising component for high speed electronics and opto-electronic devices like solar cells, and photodetectors among others. However, the fundamental parameters and properties of InN have not been well established because of the difficulty of growing high quality samples.

Previous works on the optical properties of wurtzite InN revealed that its bandgap energy is around 1.9 eV [1]. However, recent experimental and theoretical works have shown that its optical bandgap is really around 0.63 eV at 300K and 0.67 eV at 4 K [2]. This recent discovery extends the bandgap range of the III-Nitride semiconductor family from the ultraviolet (GaN & AlN) to the near-infrared (InN). The recent discovery of InN bandgap at around 0.63 eV has sparked huge research interest in III-Nitride based semiconductors/photonics.

Thus, in order to make further progress in understanding the optical properties of InN requires more investigation of the temperature dependence of its optical properties in the near-infrared region.

2. **Experimental Method**:

The samples that were studied are thin layers of InN grown on Si subtrates using RF Molecular Beam Epitaxy (RF-MBE). The thicknesses of the InN layers produced using this method are about 100 nm.

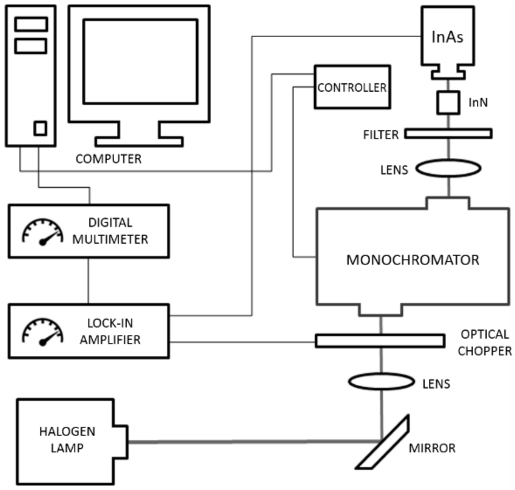

Fig. 1: Experimental setup for observing the near-infrared absorption of InN.

For this study the Tauc method was used to observe the absorption of the InN samples. Figure 1 shows the experimental setup used to measure and observe the bandgap energy of InN. The infrared light source was provided by a halogen lamp. A photovoltaic Indium Arsenide (InAs) detector was used to measure the near-infrared absorption of InN in the 1500 to 2800 nm range. At the preliminary stage, we used an Andor iDus 420 InGaAs CCD detector for convenience. The light was focused on the entrance slit of the monochromator and to the sample using quartz lenses and filtered with a 1500 nm long pass filter to remove any residual luminescence. Sample temperature was varied using an Iwatani Industrial CryoMini coldhead cryostat between 4 and 300 K during absorption measurements. Light from the halogen lamp was chopped at 80 Hz and a lock-in amplifier was used to detect the voltage absorption signal. Such a setup allows for the reduction of background noise. A Jasco CTC-25C monochromator attached to a controller was used to automatically select narrow band wavelengths of light from the 1500 to 2800 nm range. The data were then collected and plotted for analysis.

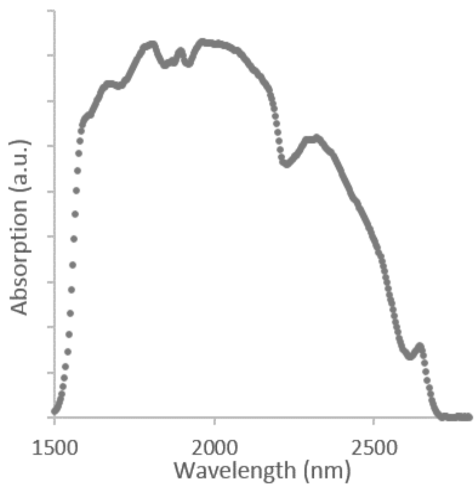

Fig. 2: The absorption spectrum of InN at room temperature (300 K) .

3. Discussion and Results:

The Tauc method, or measuring the bandgap through optical absorption, is the most popular technique in determining the bandgap of a semiconductor. By measuring the absorption of different wavelengths of light through a material we would be able to determine possible electronic transitions within the material. Figure 2 illustrates the spectrum obtained from InN at 300 K. From this, the absorption coefficient for photons above bandgap energy in a direct-gap semiconductor with parabolic bands is determined by:

$$I = A\sqrt{hv - \mathrm{E_g}} \tag{1}$$

Where *hv* is the photon energy and Eg is the bandgap of the material and *A* is the constant related to the effective mass of the material [3]. This equation shows us that the square of the absorption coefficient is linear with that of the photon energy and that the intercept of the *I* versus *hv* plot points to the bandgap of the material or sample being measured.

Figure 3 shows the optical absorption of three different InN samples at room temperature. Though the samples used in this research were grown by the same technique, slight variations in the absorption properties of the materials were observed.

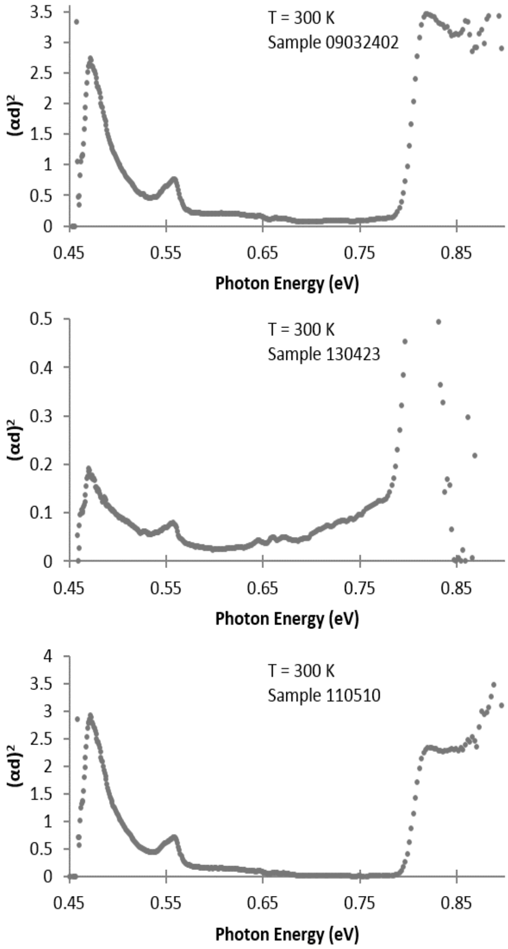

Fig. 1: Optical absorption at the near-infrared region of different samples of InN at 300 K.

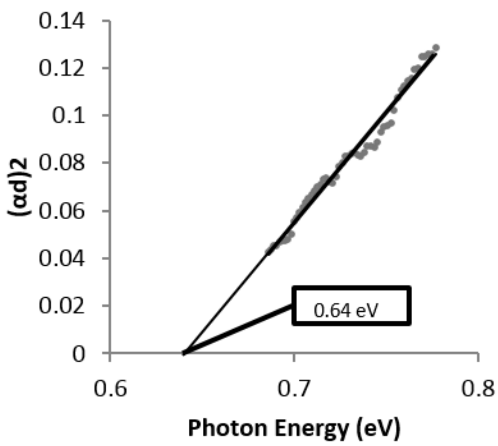

Fig. 4: Bandgap of InN at 300 K.

Sample 130423 has a relatively smooth line from the 0.68 eV to the 0.78 eV region, taking the intercept we get the bandgap for this sample to be around 0.64 eV as shown in Fig. 4.

Interestingly, the obtained bandgap energy value is near the currently accepted value of around 0.63 eV at room temperature.

Plasma reflection is also noted to be observed for the samples tested. The characteristic nature of the absorption spectrum produced by the free carrier effect is called plasma reflection. The threshold of plasma reflection is given by plasma frequency:

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon m^*}} \qquad (2)$$

Figure 3 shows that the plasma reflection edge peaks around the 0.46 eV region and drops afterwards. The 0.55eV peak might be caused by transition from the Fermi energy level of the InN conduction band to the Si conduction band edge. The 0.46 and 0.55 eV peak positions does not seem to be affected by changes in temperature as shown in Fig. 5. However, the peak height does have temperature dependence with the reflection peak

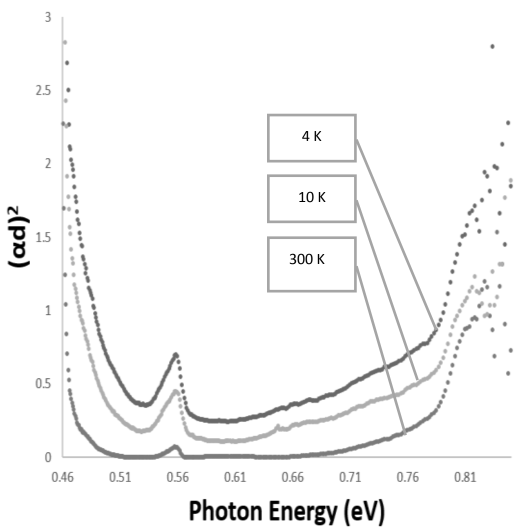

Fig.5: Absorption energy of InN at 4 K, 10 K and 300 K.

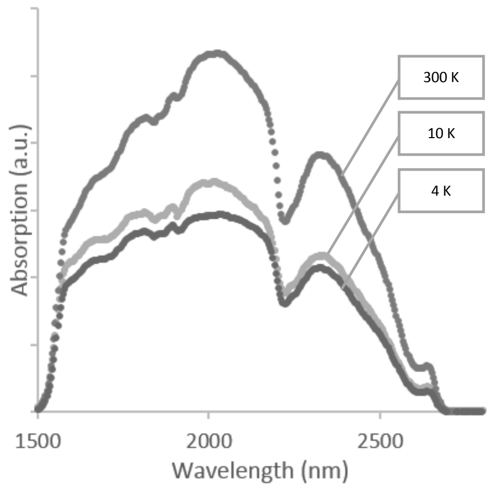

Fig. 6: Transmission spectra of InN at 4 K, 10 K and 300 K.

becoming more pronounced and steeper as the temperature decreases.

Temperature dependence of absorption in InN is also observed. Slight variations in the lineshape of the curve show little dependence on temperature with the peak red shifting and weakening as the temperature is decreased

The peak at the 0.56 eV region also exhibits an assymetric lineshape suggesting quantum interference between the conduction band in Si and that of InN. This is called as the Fano effect and it occurs through quantum interference and resonance [5]. The Fano interference has been found in a number of other experiments like atomic photoionization, electron and neutron scattering and Raman scattering. This interference leads to the typical assymetrical Fano line in the linear absorption spectra. In this case, we specualte that the 0.56 eV peak may have been induced by quantum interference between the conduction bands of Si and InN.

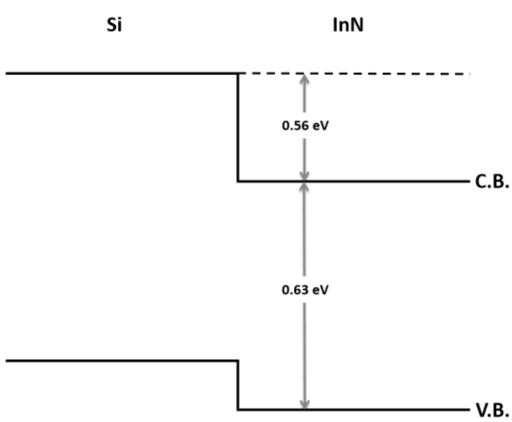

Fig. 7: Model for donor-acceptor transition in InN.

4. Summary

Temperature dependence on the properties of InN grown by RF-MBE on Si were observed and studied. Bandgap is found at 0.64 eV for wurtzite structure at 300K. Plasma reflection edge at 0.46 eV region was observed. Peak positions does not seem to be affected by temperature changes. A pronounced peak at the 0.55 eV region is suspected to be caused by transition from the InN conduction band transferring to Si conduction band. The asymmetrical line shape of this peak could be attributed to the quantum interference between the conduction band of Si and InN.

Acknowledgements

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