Photoluminescence study of undoped GaAs at temperatures 300 K and 77 K

V F Amaliya1,*, A Yuniati1,* and P van Dommelen2

1Department of physics, UIN Sunan Kalijaga, Jalan Laksda Adisucipto, Catuntunggal, Yogyakarta 55281, Indonesia.
2Department of physics, Prince of Songkla University, 15 Karnjanavanich Rd., Hat Yai, Songkla 90110, Thailand

*Email: virginiafahrizaa@gmail.com, anis.yuniati@uin-suka.ac.id

Abstract. This work presents an experimental study of photoluminescence spectra from GaAs thin layer at temperature 300 K and 77 K. PL spectra were used to investigate the characteristics of the material, such as the photon energy, gap energy, and the type of radiation transition. The apparatus used in the experiment are green laser with a wavelength of 532.0 nm, laser power supply, 500 mm focus lens, ocean optics USB 2000 spectrometer, fiber optic cable, USB cable, and the computer software installed ocean view and origin pro. The characterization was carried out at temperatures of 300 K and 77 K with power variation in the range 40 mW - 150 mW. The emitted spectrum was analyzed by observing the wavelength and calculating the photon energy and the gap energy. The results showed that laser power variation does not affect the emitted wavelength. However, it is affected by temperature. The emitted wavelength is 840 nm at 300 K and 790 nm at 77 K. The value of gap energy at 300 K is 1.422 eV while at temperature 77 K is 1.519 eV. The photon energy at temperatures 300 K and 77 K were 1.465 eV and 1.560 eV, respectively. The type of transition is a band-to-band transition at 300 K and Free Exciton (FE) at 77K. These results are consistent with existing theories, so the characterization of undoped GaAs has done successfully.

1. Introduction

Direct semiconductor such as GaAs has different electrical and optical properties compared to silicon[1]. GaAs is relatively insensitive to overheating because it has wider bandgap energy and tends to make less noise on electronic circuits, especially at high frequencies. The preparation of GaAs sample in this experiment was grown by Molecular Beam Epitaxy (MBE). The growth of layers from the molecular beam epitaxy is almost independent of the melting point, so it is possible to grow GaAs to form hetero-related relationships. The hetero-structure formed in GaAs material with other materials can be used for quantum device[2-4]. GaAs-based quantum well structures have the potential for laser applications that can emit infrared wavelengths[5, 6].

The properties of insulators or conductors of GaAs semiconductor materials can be observed through their characteristics[7]. Photoluminescence (PL) as non-destructive methods is a useful technique for observing the electrical properties of GaAs. The technique is used without contact and does not damage the material[8]. The FWHM (Full Width at Half Maximum) of PL spectrum can be used to analyze the types of radiation transition and bandgap, that might be useful for investigating carrier recombination that is a radiative recombination[9, 10].
In industrial applications, such as LEDs and photodiodes, GaAs is superior to Si or Ge because the formation process of electron-hole in the LEDs is reversible so that light energy will be emitted when electron-hole recombination occurs and immediately emitted when there is a forward voltage\cite{11,12}. It is necessary to have the sample ready to use without special preparation. This condition is especially true for in-line monitoring applications in semiconductor device manufacturers\cite{13}. PL measurement at room temperature is preferable because the semiconductor applications are widely used at room temperature. PL spectra from GaAs in this experiment were measured at the temperatures of 300 K (RT) and 77 K (lattice temperature) by varying the laser power range of 40 mW-150 mW. The effect of temperature and laser power on the change of PL spectra was investigated.

2. Experimental Methods

PL optical devices are designed to collect maximum light. The design and setting up the apparatus for the characterization of thin films is illustrated in figure 1. PL spectra of GaAs thin film were measured using 532.0 nm green lasers by varying the power from 40-150 mW. The laser beam was focused on the small sample (10 mm x 10 mm in size).

The PL signal was passed through a 500 mm filter and an SF220SMA-1064 fiber collimator adapter with fiber optic cable that transmitted the signal to the ocean optics spectrometer USB2000+. The PL spectra are then displayed on the PC screen using oceanview software. The sample was mounted on the cold finger of a closed-cycle liquid helium (He). The temperature of the cold finger was 77 K.

![Figure 1](image)

**Figure 1.** The design and setting up the apparatus for the characterization of GaAs thin films.

3. Results and Discussion

3.1 Temperature dependence of PL spectra.

PL spectra measured at temperatures of 300 K and 77 K in the power range of 40mW - 150 mW and plotted in figure 2(a) and 2(b). The wavelength was indicated as the first x-axis and the photon energy converted from wavelength was used as the second x-axis, on the top of the graph.
Figure 2. The PL spectra as a function of intensity, wavelength (nm), and photon energy (eV) with the variation of laser power at 300 K (a) and 77 K (b).

The wavelength slightly changes in unstable values by increasing the laser power, as shown in figure 2(a) and 2(b) with the emitted wavelength is 840 nm at 300 K and 790 nm at 77 K. The PL intensity at 77 K is higher than 300K. The maximum PL intensity changes sharper as the laser power increases. The higher the intensity of the light source provided, the more photons that interact one to each other. The photon's interaction will increase the intensity of photons as a function of the wavelength spectrum. The wavelength of the PL spectrum shows significant changes with temperature. The central peak is in the position near 1,465 eV (~845.58 nm) at a temperature of 300 K as shown in figure 2(a), and near 1,560 eV (~796.68 nm) at 77K as shown in figure 2(b).

3.2 Transition radiation mechanism.
Optical transitions do not require much change in both energy and momentum for direct semiconductors such as GaAs. A two-step process is not necessary because the end of the valence band (VB) and the conduction band end (CB) occur at the same momentum value[14] as shown in figure 3[6]. Thus, the absorbed photons can regenerate electrons in the conduction band and holes in the valence band, then the radiation recombination occurs. The recombination of photons which emitted various energies is referred to radiative recombination, while non-radiative recombinations are not[10].
Figure 3. Schematic illustrations of radiative recombination in GaAs.

The wavelength and photon energy of the emitted photons are determined by the radiation transition and the related phonon energy. The photon energy will exceed the bandgap when a phonon is absorbed during photon emission. The photon wavelength and photon energy will be reduced by the amount of phonons emitted from bandgap energy[13, 15].

Figure 4. Radiation transition observed with PL.

Figure 4(a) shows that PL is dominated by band-to-band recombination at room temperature[10, 16]. When a photon produces an electron pair, the Coulomb attraction can drive conditions where electrons and holes remain attached to a position called free exciton (FE). The FE energy is slightly smaller than the band-to-band energy needed to create the electron-hole pairing separation (figure 4(b)). In figure 4(c), a free hole can recombine with a neutral donor to form a positively charged exciton ion or what is called a Bound Exciton (BE), in the same way, a free electron can recombine with a hole in a neutral acceptor (figure 4(d)). The electrons in neutral donors can combine with holes in neutral acceptors (DA), as shown in figure 4(e)[10].

3.3 Normalized PL spectra.
Temperature dependence of normalized PL spectra from thin films GaAs in the temperature of 300 K and 77 K are plotted in figure 5. The temperature dependence of normalized probability distribution shows similar trends with the PL spectra. The normalized probability distribution curve provided a general idea of PL spectra at different temperatures and the effect of temperature on PL spectra.
Full Width at Half Maximum (FWHM) can be used to determine the type of transition. The bound exciton transitions are \( \leq kT/2 \) and slightly resemble the broadened delta function[10, 17], while for the valence band donor transition, the FWHM is usually a few \( k/T \) in width. There are two peaks (e, h) and (D, A) around 1,499 eV and 1,467 eV at 300 K, and 1,564 eV and 1,559 eV at 77 K, as shown in figure 5, determined respectively as band-to-band and Free Exciton transitions (FE). The first peak is determined as a band-to-band transition calculated from FWHM \( \geq 100 \text{ MeV} \), while the second peak is slightly below the band-to-band energy to form an electron-hole pairing separation.

The temperature dependence of the gap energy for many semiconductor materials has been fitted by Varshni’s empirical relation[18]:

\[
E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}
\]

where \( E_g(0) \) is the energy gap at 0 K, \( \alpha \) is the electron current constant, and \( \beta \) is the drift current constant. \( \alpha \) and \( \beta \) for GaAs are 5.405x10\(^{-4} \) eV and 204 eV respectively[16]. According to the equation, the \( E_g \) at 300 K is 1.51 eV, while at 77 K is 1.42 eV. The change in the bandgap is on the order of phonon’s energy, and the absorption or emission of a combination of a phonon(s) is accompanied in a photon emission (e-h pair radiative recombination), that is difficult to predict accurate PL spectra. However, it is possible to analyze the PL spectra and gain additional information on materials.

4. Conclusion
The design and setting up apparatus for the characterization of GaAs thin films under 532.0 nm green laser excitation over the power range of 40 mW-150 mW has been carried out based on the principle of photoluminescence (PL). The changes in PL’s intensity, wavelength, and FWHM are determined as a function of temperature. The PL intensity at a temperature of 77 K is much higher than 300 K. The radiation recombination process of GaAs is identified as a band-to-band transition for the first peak and a free exciton (FE) for the second peak.

The results showed that laser power variation does not affect the emitted wavelength. However, it is affected by temperature. The emitted wavelength is 840 nm at 300 K and 790 nm at 77 K. The value of
gap energy at 300 K is 1.422 eV while at temperature 77 K is 1.519 eV. The photon energy at temperatures 300 K and 77 K were 1.465 eV and 1.560 eV, respectively. These results are consistent with the existing theories.

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