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Optical Imaging of Diffusive Electrons with Different Kinetic Energies in a Semiconductor

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Author's Summary: When electrons in a semiconductor are generated by light, they can diffuse for a certain distance before being recombined. The length of diffusion is indicative of the material quality but, unfortunately, the motions of the electrons are difficult to observe directly. The focus of this project was to find a simple and effective way to measure the diffusion length of electrons in a semiconductor material. A laser was used to generate electrons in a small area and an imaging camera was used to map their distribution through the light they emitted as they diffused. This technique can be implemented to quickly and accurately assess the quality of any semiconductor material.

Abstract

In this project, a photoluminescence (PL) imaging technique was developed for probing electron diffusion in a semiconductor thin film. This technique was applied to investigate electron diffusion in GaAs for electrons of different kinetic energies. A tightly focused laser beam at 532 nm was used to generate electrons in an area of about 0.72 μm, and the spatial profile of the PL in an area much larger than that of the laser excitation site was imaged by a digital camera. Analysis of the PL images at different wavelengths indicated that the electrons maintain the same thermal distribution during diffusion and exhibit a common diffusion length of approximately 3.5 ± 0.2 μm.

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Introduction

When a solar cell is illuminated by light, free electrons are generated in the semiconductor. They need to diffuse to an electrode (anode) in order to be collected to produce a current. A quantity called the electron diffusion length (EDL) is used to measure the material quality. The EDL is how far an electron can travel before it is depleted by various possible mechanisms, such as giving its energy back to a photon or being captured by a defect in the material. One simple way to measure the EDL is to generate a high density of electrons in a small region of a thin semiconductor slab using a tightly focused laser beam, then watching how these electrons diffuse away from the generation site due to the presence of a concentration gradient [1]. By passing a laser beam through an optical microscope with a high magnification and high numerical aperture lens, the laser can be focused on the sample surface with a minimum spot size. This is known as the Abbe diffraction limit [2], with a diameter determined by the equation

$$d = 1.22\lambda/NA$$

where λ is the laser wavelength and NA is the numerical aperture of the lens. Typically, for visible light, a spot size below one micrometer (less than 1% of the width of a typical human hair) can be achieved. The microscopic phenomenon of the electron diffusion resembles a macroscopic one: pouring a bucket of water onto a surface and watching how far the water flows. If a semiconductor is nearly free of defects, the electron diffusion length can be up to 100 μm in a high-quality GaAs sample [3].

One of the depletion mechanisms for the electrons generated by light is the reemission of light. This process is called photoluminescence (PL), which results from the electrons falling back to the lower energy states where they were before being pumped up to the conduction states by the laser light. The PL intensity is proportional to the electron concentration. Therefore, by measuring the intensities of the PL signal at different distances from the illumination site, a relative spatial distribution of the diffusing electron concentration can be obtained. The EDL is an important parameter that measures the perfectness of a semiconductor crystal because the electrons will diffuse farther in a better semiconductor crystal.

The general approach of PL imaging is to use a digital camera to record an image of the PL signal in the vicinity of a small laser

illumination spot. The variation in the brightness of the image is a direct measure of the spatial variation of the PL signal, which in turn correlates to the spatial variation in the electron concentration. The schematic of the PL imaging technique adopted in this work is shown in Figure 1. After the PL imaging data is obtained, a computer code, written in Wolfram Mathematica, is used to extract the electron diffusion length. The spatial profile of the PL image is the solution of a diffusion equation including a generation term and a depletion term [4, 5, 6]. It is usually a decay function of r with a parameter L, where r is the lateral distance measured from the generation site at r = 0; L is the electron diffusion length, assuming that the semiconductor is very thin and diffusion occurs only laterally.

For a semiconductor, there is a minimum energy that is needed to generate conduction electrons. This energy is referred to as the band gap energy. When the photon energy is much higher than the band gap energy, "hot" electrons are generated initially in the semiconductor. However, the hot electrons quickly lose energy to the lattice and approach the lower energy states near the band gap in what is known as an energy relaxation process. In the meantime, they also diffuse away from the generation site, just like the "cold" electrons near the band gap. Because of this energy loss, it might be expected that the hot electrons would diffuse less than the cold ones. However, at room temperature, the electrons also gain thermal energy from lattice vibrations to be repopulated to the higher energy states. In other words, they have different kinetic energies and are distributed over a range of energy states. At high temperatures, due to these rapid thermalization processes, they typically follow a Boltzmann distribution [7].

The goal of this project was to find out whether electrons of different kinetic energies have the same diffusion length. This question had not yet been answered by previous studies. The hypothesis was that the electrons with different kinetic energies would have the same diffusion length because of rapid thermalization processes at room temperature, in particular when the generation source was continuously applied as occurs with the continuous wave (CW) laser that was used for the PL imaging measurement. The answer to this question is important in solar cell design for efficient electron collection. Because electrons with different kinetic energies emit photons at different wavelengths, the spatial variation of the PL signal for different wavelengths had to be measured and compared to test the hypothesis. In previous studies, both electron and laser beams have been used to generate a local electron population, but the spatial profiles of light emission were typically measured either by including the whole emission spectrum (non-wavelength selective) [5] or by selecting a single narrow band near the bandgap [6, 8, 9, 10]. Thus, the potential wavelength dependence had not been explicitly examined. For this study, the EDL of electrons with different kinetic energies was measured using a simple new method.

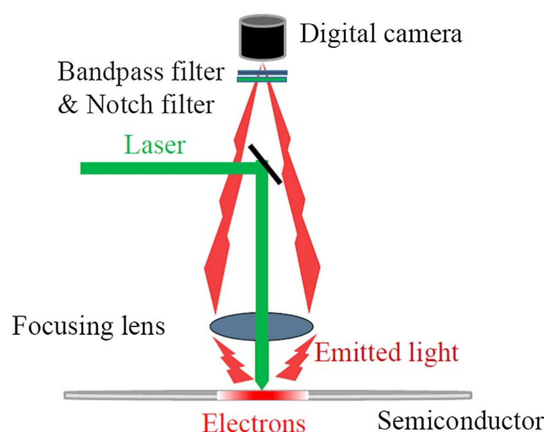

Figure 1. Schematic for PL imaging of electron diffusion in a thin semiconductor film.

Materials and Methods

This experiment was conducted using a confocal optical Raman microscope (Horiba LabRam HR800). The system was not designed for, nor was it capable of, performing the required measurements, because the intensity distribution beyond the laser illumination site needed to be imaged simultaneously, and the system could only measure the signal of the illumination site in the standard confocal mode. Thus, an innovative method was developed. The imaging camera, which was normally used for monitoring and visually examining the sample, was used to capture the PL image. An adaptor for holding filters was made and mounted in the optical path to the camera. To accomplish the wavelength selection, a bandpass filter was placed on the adaptor before the camera. Each bandpass filter allowed only a narrow bandwidth of light to pass through while blocking all other wavelengths in the PL signal. Additionally, a notch filter, which blocks the laser wavelength but allows other wavelengths to pass through, was needed to further reduce the interference of the scattered laser light at 532 nm.

The semiconductor sample used was a 1 μm thick high-quality GaAs (gallium arsenide) thin-film sandwiched between two GaInP (gallium indium phosphide) layers with a higher bandgap [6, 8, 9]. GaAs was chosen because of the availability of the high-quality sample as well as its important role in many technology applications, including high efficiency solar cells, semiconductor lasers, and high-speed electronics. At room temperature, GaAs emits light in near infrared (approximately 800–900 nm) with a peak near its band gap of 870 nm. A set of bandpass filters, each with a 10 nm bandwidth, was used to acquire PL images at selected central wavelengths, such as 830, 850, and 870 nm. The wavelength dependence of the diffusion length could then be extracted by analyzing the PL images of different wavelengths.

Results

The PL spectrum of GaAs and one typical 3-D PL image at 830 nm are shown in Figure 2. This PL image reveals the spatial profile of the PL signal that exhibits an intensity maximum at the center (the laser illumination point) and decays quickly with increasing distance from the center. This image was achieved by continuously illuminating the sample at the center with approximately 1 mW of laser power.

The normalized intensity profiles (a line scan passing the center of the excitation site) are compared in Figure 3 for three wavelengths at 830, 850, and 870 nm obtained under the same laser power. It is important to make such comparisons under the same laser power because it has been shown in previous work that the diffusion length is sensitive to the excitation power [6, 8, 9]. Clearly, the three profiles are quite close to each other, which indicates that the diffusion lengths for electrons of different kinetic energies are approximately the same. The correct function for describing the profile should be a modified Bessel function [4, 5, 6] but corrected for the final laser spot size, which requires solving the diffusion equation numerically. As an approximation, a simple exponential decay function ($e^{-r/L}$) was adopted. The 1/e point of the

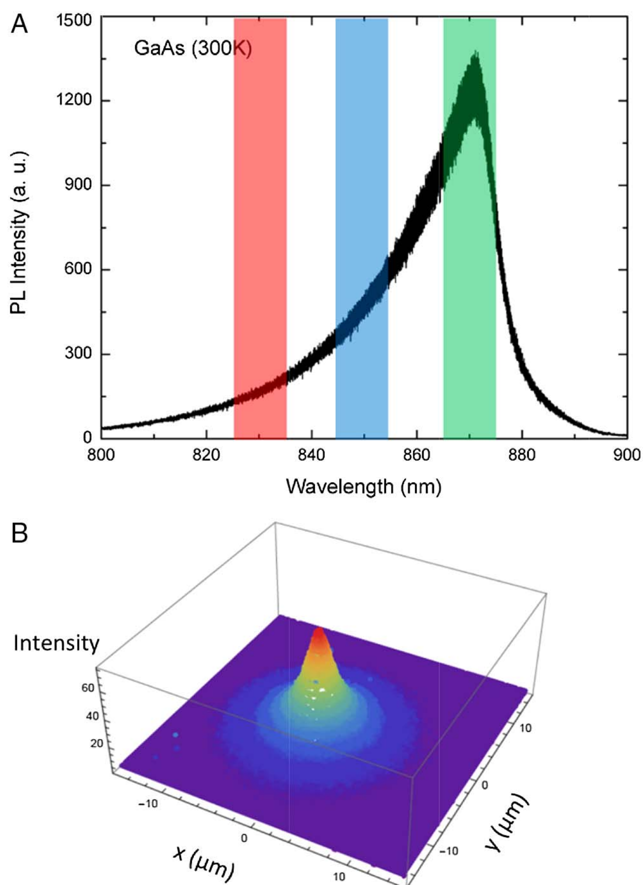

Figure 2. (A) PL spectrum of GaAs with three imaging spectral windows indicated. (B) 3D plot of a PL image at 830 nm generated by a focused 532 nm laser at the center (0,0).

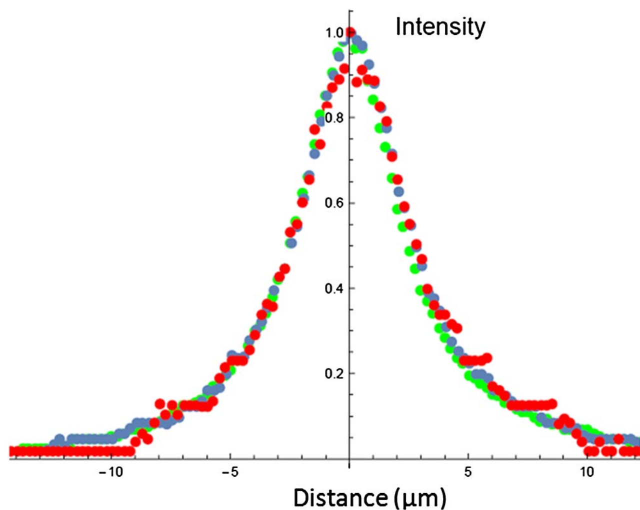

Figure 3. Line profiles of PL images at three wavelengths: 830 nm (red), 850 nm (blue), and 870 nm (green).

decay function yields the value L = 3.5 ± 0.2 μm for all three wavelengths. This finding confirms the hypothesis that electrons with different kinetic energies have similar EDLs. Fitting the data with the more complex profile function could yield somewhat different values for the diffusion lengths but would not affect the general conclusion.

Discussion

A commercial micro-Raman microscope was modified to perform photoluminescence (PL) imaging and obtain the spatial distribution of PL signal generated by a tightly focused laser beam with a diffraction limit spot size (0.72 μm for a 532 nm laser). The PL spatial distribution can be directly related to the distribution of electron density resulting from outward diffusion of the electrons generated at the excitation site. By inserting different narrow bandpass filters, the PL spatial distribution can be spectrally resolved at different wavelengths that correspond to different electron kinetic energies. This technique was applied to investigate electron diffusion in GaAs. The analysis of the PL images at different wavelengths indicated that the electrons in the energy range of significant population (up to 2.6 kT above the bandgap) maintain the same thermal distribution during the diffusion and exhibit a common diffusion length (3.5 ± 0.2 μm).

The current results are only accurate for a short diffusion distance (and thus for the majority of the photo-generated electrons) because of the limited dynamic range of the camera (intensity scale of 0–256 or 8 bits). Also, the current study only covers an energy range about 68 meV above the bandgap, which is about 2.6 kT of the thermal energy. In the future, improving the dynamic range will allow more careful examination of electron diffusion at a longer distance and higher energy. Furthermore, simultaneously spatial- and time-resolved measurements are needed to investigate the electron diffusion process as a function of PL emission energy to obtain diffusivity and decay time separately [11], and to compare with the CW measurement carried out here.

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