OPTICAL PROPERTIES OF SEMICONDUCTORS

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Abstract *– A computer based laboratory experiment in the physics lab for students of communications engineering, computer engineering and software engineering is described. The aim of the experiment is to bring the students at an early stage into practical contact to modern physics such as semiconductors, wave and quantum optics, and to gain a deeper understanding of the mechanisms of absorption and emission of light by semiconductors. The actual experiment is divided into three parts: After getting acquainted with the experimental set-up by calibrating the spectrometer the students measure the absorption coefficient in gallium phosphide and finally some emission spectra of different LEDs.*

INTRODUCTION

Esslingen University offers engineering degrees in different fields of professional engineering. The education regularly takes four years divided into eight semesters. Since physics, along with calculus, chemistry and some other subjects, is considered to be the basis of modern technologies our students attend lectures in experimental physics in their first two semesters. Usually such a course is supplemented by laboratory experiments which are conducted by the students.

The experiment described in this paper was developed for students of communications engineering, computer engineering and software engineering. In their first semester they attend a physics lecture of three periods (3×90 minutes) per week which mainly deals with mechanics. In the second semester the lecture is two periods per week and covers waves, some quantum mechanics and solid state physics, especially semiconductor physics. During the second semester the students have to do four laboratory experiments. Each experiment takes about three hours and is carried out by two students. A detailed laboratory report must be completed and has to be submitted two weeks after the performance of the experiment.

For the students of communications engineering and computer engineering a sound knowledge of the properties of semiconductors is of great importance. Therefore, besides the classical mechanical experiments we introduced two experiments that cover this topic. One apparatus is designed to measure the Hall effect and some basic properties of semiconductors, the other one which is described in this paper deals with the optical properties of semiconductors. Particularly those students who intend to specialize in optoelectronics, which is one of the electives offered in higher semesters, take advantage of a deeper understanding of the interaction between light and semiconductors.

CALIBRATION OF THE SPECTROMETER

The optical key instrument of the equipment shown in figure 1 is the spectrometer. It is a monochromator of Cerny-Turner type with a focus length of 22 cm. The grating is 50 mm wide and is ruled with 1200 grooves/mm; it is blazed for 500 nm. The grating can be rotated manually by means of a turning knob at the front of the housing. The transmitted wavelength can be read from a wavelength indicator. The monochromator is equipped with exchangeable slits of fixed width.

From the accompanying lecture the students know about the dispersive properties of a diffraction grating. However, they have in general never worked with a commercial instrument before and therefore it is important that they become acquainted with it. Thus, after the supervisor has explained the main features to them, they have to calibrate the wavelength read-out. This is done by focussing a low pressure mercury lamp onto the entrance slit of the monochromator as shown in figure 1. The wavelengths of the spectral lines of mercury are well known from literature [1] and listed in table I. By turning the wavelength knob the grating is positioned so that the light of e.g. the prominent green line at 546.1 nm is fully transmitted through the exit slit. The found read-out of 546.6 nm is the actually measured wavelength of the spectrometer. A compilation of typical results for the different wavelengths is presented in table I. As the measuring errors appear to be within a bandwidth of ± 1 nm, which is just the specified accuracy, the instrument is considered as being adjusted satisfactorily.

The calibration procedure is done purely “by hand” while the intensity of the transmitted light is judged by the human eye. Of course, this measurement could be accomplished also with the aid of the photodiode and the amplifier which will be used later anyway. However, we think that it is very important for the students to experience physics not only by means of computer controlled machines but also by manually handling and playing with things and using the human senses instead of electronic sensors. A much better feeling and understanding of the performance and the limits of an instrument is thus gained.

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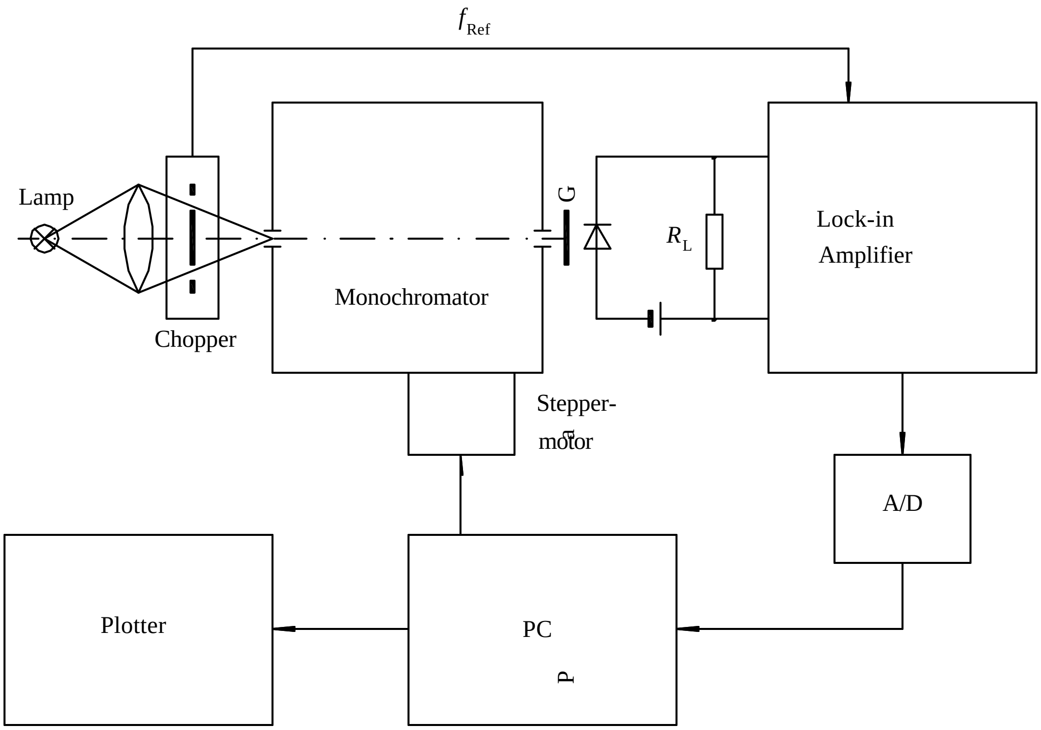

FIGURE 1
BLOCK DIAGRAM OF THE EXPERIMENTAL SET-UP

TABLE I
WAVELENGTHS OF SPECTRAL LINES OF A LOW PRESSURE MERCURY LAMP. COMPARISON BETWEEN THE MEASURED VALUES AND THOSE TAKEN FROM THE LITERATURE [1]

Reference wave-length, l_r/nm	Measured wave-length, l_m/nm	Measuring error (l_r - l_m)/nm
579.1	579.6	-0.5
577.0	577.1	-0.1
546.1	546.6	-0.5
491.6	490.8	0.8
435.8	434.3	1.5
407.8	407.1	0.7
404.7	404.5	0.2

ABSORPTION OF LIGHT

Theory

The students know from the accompanying physics lecture that in single atoms electrons may occupy only well defined “allowed” energy states. In solids the electrons do occupy more or less broad allowed bands separated by “forbidden” gaps. A simple energy-band scheme of a semiconductor is depicted in figure 2. At temperatures close to 0 K, the highest valence band is filled with electrons. The next higher allowed band, the so called conduction band is empty. The two bands are separated by an energy gap of width E_g. This gap is a fundamental quantity of the semiconductor and influences many properties of the material. Therefore, one of the tasks of the students is the determination of the band gap. At room temperature a considerable number of electrons has been lifted from the valence band into the conduction band leaving holes in the electron sea of the valence band. The necessary energy is gained from thermal movement.

A transition of electrons from the valence band into the conduction band can also take place if the required energy is supplied by radiation. According to Einstein’s theory, radiation can be considered as a flow of optical quantum particles called “photons”. Each photon carries a certain amount of energy which is proportional to the frequency, *n*, of the electromagnetic wave and is given by

$$E_{\text{ph}} = hn = h\frac{c}{l}; \qquad (1)$$

h being Planck’s constant, *c* the velocity of light and *l* the wavelength [2]. It becomes clear that light can only be absorbed in a semiconductor if the energy of the photons is larger than the band gap, i.e. $E_{\text{ph}} \geq E_g$. In other words: the wavelength of the light must be smaller than the wavelength l_g that corresponds to the energy gap, E_g:

$$l \leq l_g = h\frac{c}{E_g}. \qquad (2)$$

If this condition for absorption is met, it appears that the optical power of the light wave, *F*, is exponentially reduced while travelling through the crystal. If the power which is coupled into the crystal is denoted by F_0, the transmitted power that leaves a crystal of thickness d is given by

$$F = F_0 \exp\left(-a\, d\right). \qquad (3)$$

a is called "absorption coefficient" and has to be determined by the students. From (3) it follows that

$$a = -\frac{1}{d}\ln\left(\frac{F}{F_0}\right). \qquad (4)$$

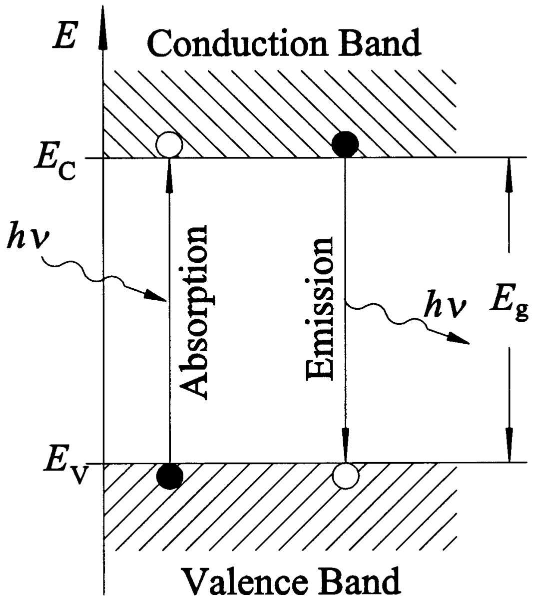

FIGURE 2
PROCESSES OF LIGHT ABSORPTION AND EMISSION REPRESENTED IN THE ENERGY-BAND SCHEME OF A SEMICONDUCTOR

Experiment

The block diagram of figure 1 shows that the light which is being transmitted by the monochromator falls on a silicon photodiode. The signal is fed into a lock-in amplifier which is tuned to the reference frequency of a mechanical chopper. This lock-in technique is widely used in optics to enhance the signal-to-noise ratio. After analog-to-digital conversion the data are fed into the computer via an IEEE 488 bus. The grating of the monochromator is turned by means of a stepper motor which is activated via I/O card from the PC.

In order to measure the absorption coefficient according to (4), the quotient $\left(F/F_0\right)$ is needed. Therefore, a first spectrum which is denoted $F_0(l)$ is measured without a semiconductor in the optical path. As for the investigated material gallium phosphide (GaP) the band gap is close to 2.25 eV, the interesting wavelength region is from 500 to 600 nm. Next the crystal of thickness d = 0.45 mm is put close to the exit slit and the amplifier is adjusted so that the signal at 600 nm is identical to the signal measured without the semiconductor. The justification of this adjustment is given by the fact that for wavelengths well above the fundamental edge, l_g, absorption does not take place. However, as GaP like all semiconductors has a high index of refraction (n ≈ 3.28 @ 600 nm, [3]) it exhibits a high reflectance (28 % @ 600 nm, [3]) and therefore the actual power levels F(600 nm) and F_0(600 nm) are not equal.

The results of the measured spectra $F_0(l)$ and $F(l)$ are plotted in figure 3 a). Figure 3 b) presents the relation $F(l)/F_0(l)$ as calculated by the computer. It seems interesting to note that the spectral characteristics of the lamp (here a tungsten lamp was used) is of no importance for the resulting curve of $F(l)/F_0(l)$.

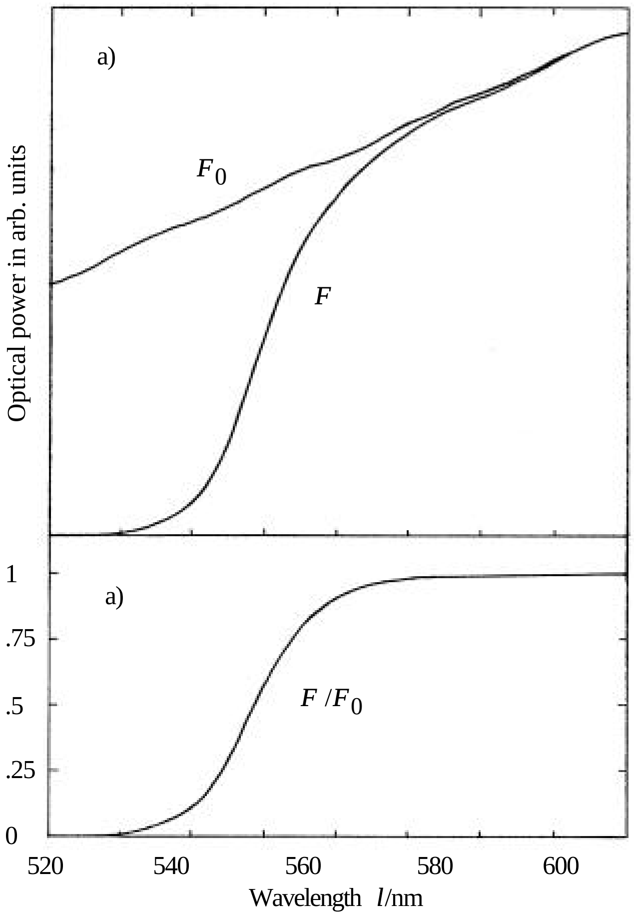

FIGURE 3
A) MEASURED SPECTRA OF THE OPTICAL POWER $F_0(l)$ WITHOUT, AND $F(l)$ WITH GAP CRYSTAL,
B) CALCULATED POWER QUOTIENT $F(\lambda)/F_0(\lambda)$

The semiconductor GaP is especially suitable for such a student experiment because the fundamental absorption edge lies in the middle of the visible spectrum and therefore the students can literally "see" the band gap of the semiconductor by looking through the crystal against white light. It appears that GaP has got a reddish-yellow color which is due to the fact that the short wavelengths of the white light (violet and blue) are absorbed and the long wavelengths (yellow and red) are transmitted. The absorption edge lies in the green region.

In their laboratory report the students have to calculate and plot the absorption coefficient, a, by using (4). A typical result is presented in figure 4. The intersection of the tangent to the $a(l)$ curve with the horizontal axis leads to $l_g \approx$ 551 nm. Accordingly, the band gap of GaP is found to be $E_g \approx$ 2.25 eV in good agreement with the literature [3, 4].

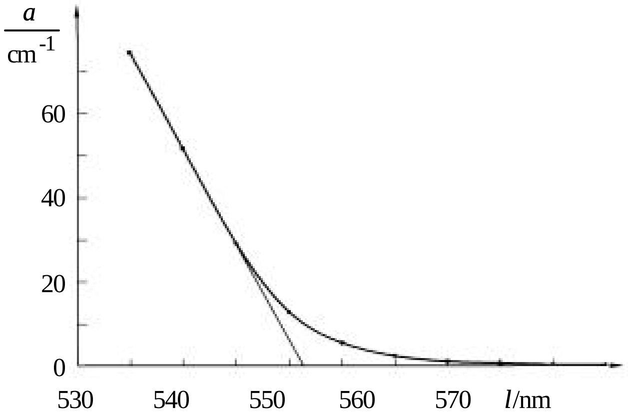

FIGURE 4
CALCULATED ABSORPTION COEFFICIENT USING THE DATA FROM FIGURE 3 B)

EMISSION OF LIGHT

Theory

The above mentioned physics course is also concerned with emission of light and the students should be well prepared for this subject. If the conduction band is filled with more than an equilibrium distribution of electrons, then electrons can fall back spontaneously into holes of the valence band. In the course of this recombination process energy is released either in form of light or heat. In the case of radiative recombination one photon is emitted for each transition as shown in figure 2.

The emission of radiation is related to the transitions of electrons from the higher energy level in the conduction band to the lower level in the valence band. The value of the energy gap, E_g, between these levels is distinctive for every semiconductor, e.g. for GaAs: $E_g \approx$ 1.43 eV. The photon energy of the radiative emission is approximately the same as the energy of the forbidden gap:

$$E_{ph} \approx E_C - E_V = E_g \; . \tag{5}$$

Hence, the center wavelength of the radiation can be calculated using (1):

$$l \approx h\frac{c}{E_g} \; . \tag{6}$$

The wavelength and the color of the emitted light consequently depends on the band gap of the semiconductor which can be controlled by techniques of crystal growth.

Furthermore, by this laboratory experiment the students should learn that there is no source which emits light at a single wavelength. It is impossible to realize pure monochromatic light, but there is always a polychromatic behavior which can be understood as follows. The considered electrons and holes show an energy distribution that resembles the density of molecules in the atmosphere which becomes thinner the higher we go. Figure 5 depicts a schematic sketch of the distribution of electrons in the conduction band and holes in the valence band. From this distribution it is clear that the emitted photons have different energies depending on the actual energies of the electrons and holes prior to recombination.

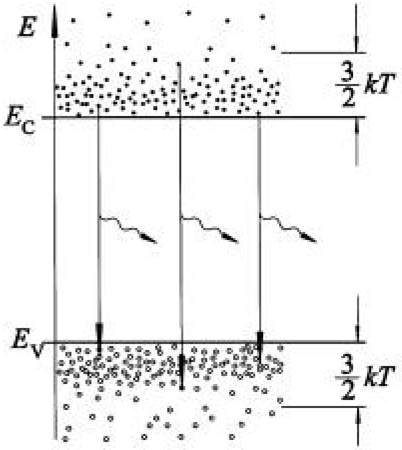

FIGURE 5
THERMAL DISTRIBUTION OF ELECTRONS AND HOLES IN A SEMICONDUCTOR

To gain a rough idea of the expected spectral line width of the emitted radiation it can be argued, following classical thermodynamics, that the distribution of electrons and holes has an energetic width of $\frac{3}{2}kT$ each, where k is Boltzmann's constant and T the absolute temperature. Therefore, the emission bandwidth is expected to be approximately

$$\Delta E \approx 3kT \; . \tag{7}$$

This energy bandwidth ΔE can be recalculated into a spectral bandwidth, Δl, in terms of wavelengths:

$$\Delta l = \frac{l}{E_g} 3kT = \frac{l^2}{hc} 3kT \; . \tag{8}$$

It can not be expected from this simple theory that the experimental line width is in perfect agreement with the prediction of (8), but it will be seen in the next paragraph that the agreement is reasonable. The correct spectral line shape for band-to-band transitions can be calculated by a convolution integral over the density of states and the Fermi-distribution functions of the electrons and holes [4]. This leads indeed to a better agreement between theory and experiment but is much too complicated for students at that stage.

The quantitative description of the bandwidth is determined by the FWHM definition (full width at half maximum). The application of a generally accepted definition by international standards is very important to make results comparable. Otherwise serious mistakes could occur. This has to be pointed out when teaching students to understand measured diagrams.

Radiative recombination is the basic underlying principle of light-emitting diodes (LEDs) and semiconductor lasers. An LED consists of a p-n junction, where in the n-doped region there is an excess of electrons in the conduction band whereas in the p-doped region an excess of holes in the valence band is registered. By applying a forward current, electrons will flow from the n-type to the neighboring p-type region and holes vice versa. This process allows a huge recombination rate of electrons and holes and leads therefore to the emission of light.

Experiment

The experimental set-up is practically the same as the one used for the absorption measurement (see figure 1), except for the replacement of the tungsten light source by the LEDs under test and obviously the GaP crystal is removed. The measurement procedure is also nearly unchanged. Figure 6 depicts the result, i.e. a plot of the optical power versus wavelength of three LEDs measured consecutively.

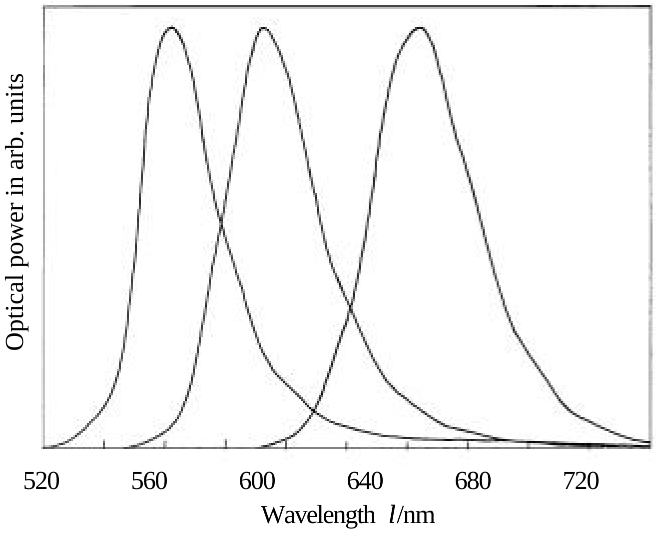

FIGURE 6
MEASURED SPECTRA OF THE OPTICAL POWER VERSUS WAVELENGTH FOR THREE DIFFERENT LEDS (GREEN, YELLOW, RED)

The measurement yields spectral bandwidths of 30, 35 and 39 nm, respectively, whereas from the calculation on the basis of (8) line widths of 20, 22 and 27 nm, respectively are expected. The agreement of the experimental result and the theoretical prediction is only of qualitative nature due to the shortcomings of the applied theoretical model as explained in the previous section. However, the students may easily verify that the line width is temperature controlled according to (8). This can be done by changing the forward current of the LED. With increasing current the temperature within the LED is raised which results in a broadening of the line width. In particular, the tendency of rising bandwidth with increasing wavelength is in good agreement with the theoretical prediction of (8).

CONCLUSIONS

The rather complex processes of the interaction between radiation and matter can be made quite clear even to undergraduate students by practical measurements of absorption and emission of light by semiconductors. The use of semiconductors whose band gap corresponds to wavelengths within the visible spectrum seems especially adequate. In this case, the students can intuitively understand the underlying principles simply by visual inspection of the colored light; i.e. students not only read out the center wavelengths of the LED emission to be 560, 590 and 650 nm, respectively, moreover they also identify the colors green, yellow and red simply by looking at them.

The success of the laboratory experiment is dependent on a good preparation of the students. Besides the accompanying lecture the students receive a comprehensive description of the physical fundamentals as well as some details concerning the experimental set-up.

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