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3. Photoelectric Effect Using Light Emitting Diodes

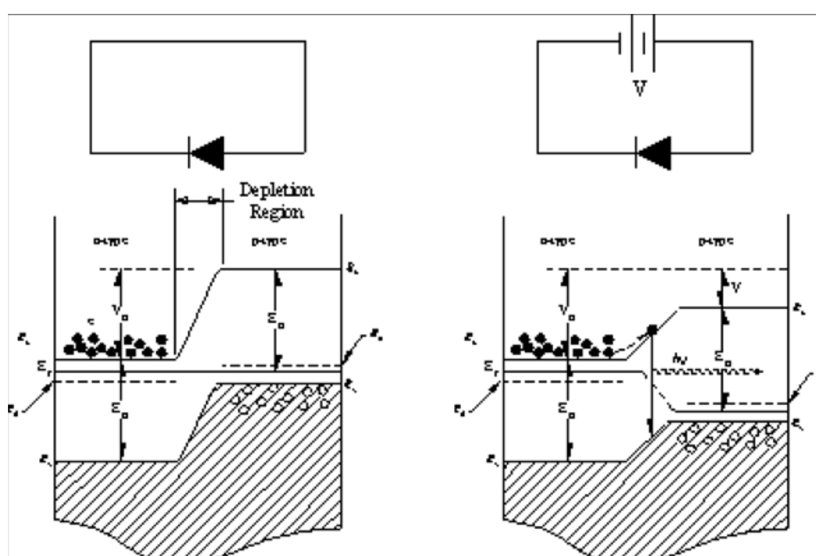
3.1 Physics of Light Emitting Diodes

The phenomenon of light emission by electrical excitation of a solid was first observed in 1907 by H. J. Round using silicon carbide (SiC). O. V. Lossev investigated these electro-luminescence effects in more detail between 1927 and 1942, and correctly assumed that they represent the inverse of Einstein's well-known photoelectric effect. The more precise description of the phenomenon is recombination emission of minority carriers injected at a p-n junction. This was given by K. Lehovec in 1951. A similar luminescent effect produced by an electric field in zinc sulfide was independently discovered in 1935 by G. Destriau, but the excitation mechanism is different from the injection phenomenon found in SiC. The ZnS electro-luminescence was the subject of some technical development effort in the 1950's.

Although the results of the ZnS development work were disappointing, success was obtained using III-V compounds that were recognized as semiconductors by H. Welker in 1951. These compounds, containing equiatomic quantities of an element from the third column of the periodic table and one from the fifth, have several remarkable characteristics when compared with the classical semiconductors silicon (Si) and germanium (Ge).

They show a wide range of band gaps E_g, some of them considerably greater than those of Si and Ge, and their frequency equivalents $\nu = E_g/h$ reach into the visible spectral region. Some of them also exhibit much higher radiative recombination efficiencies for electrons and holes and higher charge carrier mobilities than Si and Ge. The complex techniques necessary for their production under industrial conditions were only mastered at the end of the 1960s. Today they are routinely used as LEDs, semiconductor lasers, optical interfaces, and high-speed elements.

LEDs are based on the injection luminescence principle. They consist of simple p-n junction diode. Without an externally applied voltage, a diffusion potential V_D is generated in the depletion layer between the n- and p-type material (see Fig. 5(a)). The diffusion potential prevents electrons and holes from leaving the n- and p-regions respectively and entering the opposite regions. In chemical equilibrium (no external bias) the Fermi energy, E_F, is a constant across the junction. On the n-side E_F lies between the donor level, ε_d, and the conduction edge, ε_c. On the p-side E_F lies between the acceptor level, ε_a, and the valance band edge, ε_v.



(a) (b)

Figure 5. The electron energy level diagram of a p-n junction light-emitting diode. (a) unbiased diode. The solid circles are electrons and the open circles are positive holes. (b) forward biased diode. The bias voltage is V.

When an external voltage V is applied in the forward bias direction (see Fig. 5(b)), the barrier is reduced to $e(V_D-V)$. When $V \sim V_D$ the barrier is nearly zero and electrons can flow from the n-side to the p-side. As electrons are injected into the depletion region, some will radiatively recombine with holes from the p-region and emit a photon of energy $h\nu \sim E_g$.

The probability of radiative recombination depends primarily on the band structure of the semiconductor used in the diode; that is, on the momentum dependence of the energy states (dispersion relationship). Three dispersion relations are shown in Fig. 6. In a direct band gap semiconductor (Fig. 6(b)), of which gallium arsenide (GaAs) is the most important example, the maximum of the valence band (populated by holes) and the minimum of the conduction band (populated by electrons) occur at the same value of the quantum mechanical wave number vector k. The recombination process of an electron making a transition from the conduction band minima to the valance band maximum and emitting a photon must conserve both energy and momentum. Since the momentum of a photon is negligibly small, momentum conservation is not a problem for a direct gap semiconductor since $\Delta k \sim 0$. The probability of a radiative band-to-band transition is therefore very large in such materials.

In contrast, in an indirect band gap semiconductors such as silicon (Si), germanium (Ge) and gallium phosphide (GaP), the extrema of the bands lie at different wave vectors (Fig. 6(a)). Momentum conservation through the emission of a photon is not possible. Another process is needed to supply the additional momentum. The additional process is usually the emission of a phonon or a transition to an energy level caused by a lattice defect. The requirement of an additional process in the transition to conserve momentum sharply reduces the probability of radiative transitions. Instead nonradiative transitions (energy being converted to lattice vibrations through phonons) dominate in Si and Ge.

Almost all the currently available LEDs and semiconductor lasers are based on GaAs, whose band gap of 1.43 eV corresponds to an emission in the infrared region near 900 nm. When GaAs is mixed with the indirect semiconductor GaP, the resulting structure retains a direct gap up to a Phosphor content of 45%, with a corresponding band gap of about 2 eV (in the red-orange spectral region). At higher P concentrations, the structure becomes indirect, and the probability of radiative band-to-band transition falls off by several orders of magnitude. However, the use of a GaAs/GaP mixed crystals for visible LEDs is not limited to the red spectral region, since efficient radiative recombination can be achieved in GaP and the indirect regions of the GaAs/GaP system by appropriate doping.

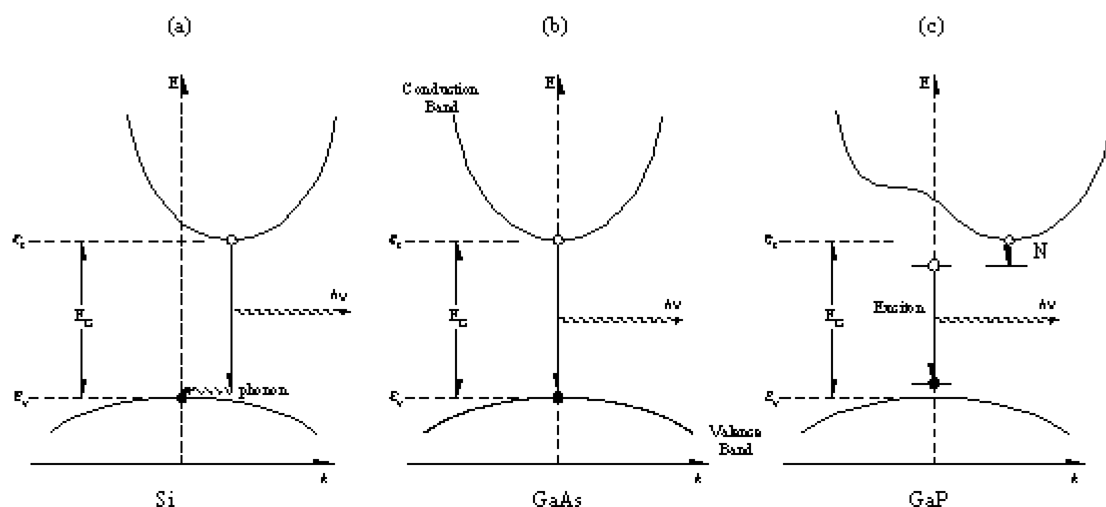


Fig. 6: Dispersion relations, E vs k, for (a) indirect band gap semiconductor. (b) direct band gag. (c) indirect band gap with nitrogen impurity level and exciton level.

This type of doping is applied by using so-called isoelectronic defects. These are lattice defects in which the substituting atoms come from the same column of the periodic table as the atoms they replace, so that they do not affect the charge carrier balance in the lattice, unlike the usual donor and acceptor atoms. However, they differ from the host atoms so markedly in atomic radius and electronegativity, that charge carriers can be bound at their sites. The best known isoelectric defect in GaAs/GaP is nitrogen, occupying an As or P site. The small radius and higher electronegativity of the N atoms allows them to bind an electron. The electron creates a hole by a Coulomb interaction, forming a so-called bound excitation. The decay of this exciton by recombination of the electron and the hole leads to the emission of a photon (see Fig. 6(c)). The advantage of isoelectronic defects lies in the strong localization of the primary bound electron, which is accompanied by a strong increase in the uncertainty of its momentum, in accordance with Heisenberg's Principle. This results in an increase in the probability of radiative recombination.

From Fig. 5(a) it is clear that eV_{Dg}. However, in most doped semiconductors the energy differences ε_c-ε_d or ε_a-ε_v are small compared to the band gap E_g. Usually ε_c-ε_d or ε_a-ε_v are a few meV while E_g can be ~ 1eV. This means that to a very good approximation (see in Fig. 5(a));

$$eV_D \approx E_g \qquad \text{Eq. (3)}$$

If we assume that, of those electrons injected into the depletion region, all of their energy supplied by the electric field is converted into light, then the frequency of that light is approximately,

$$h\nu \approx E_g \qquad \text{Eq. (4)}$$

Combining Eqs. (3) and (4) gives,

$$h\nu \approx eV_D \qquad \text{Eq. (5)}$$

Equation (5) therefore provides us a way of measuring Planck's constant. If we know the wavelength of the light emitted from the LED and we can measure the diffusion potential, then h/e is given by Eq. (5). The next section below describes how this will be done.

3.2 Apparatus & Equipment

Apparatus

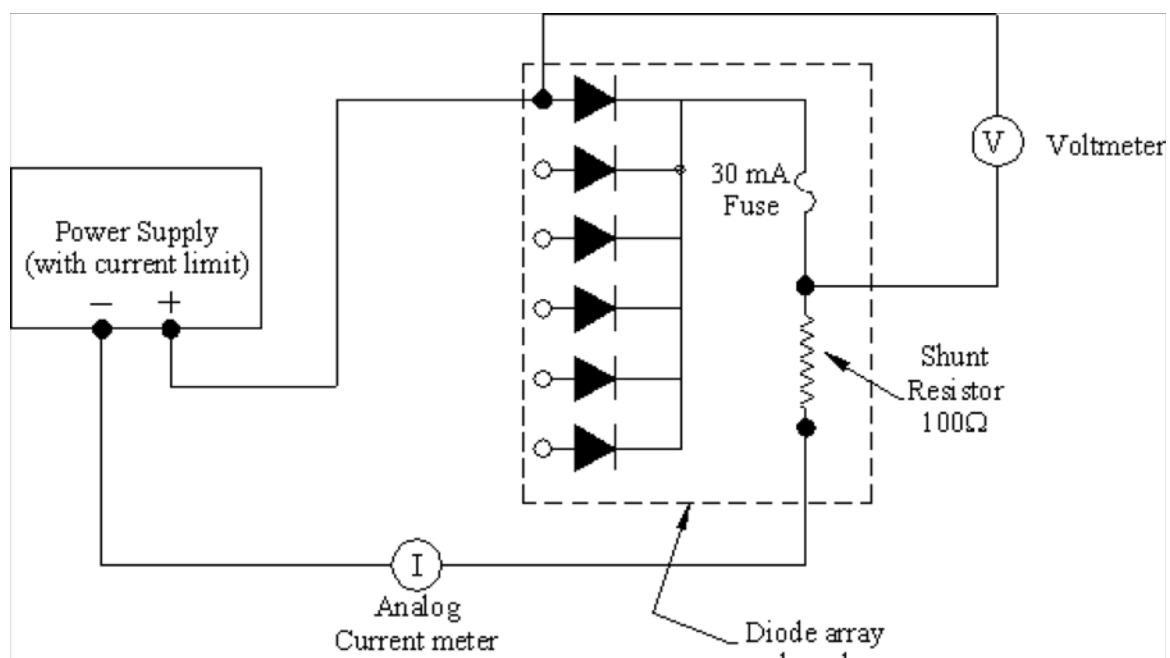


Fig. 7: Schematic drawing of the photodiode experiment.

Equipment

1. Stand and Board with six LED's, includes current limiting resistor, fused for 30 mA. See Sec. C.3.2 For diode characteristics
2. Adjustable power supply with current limit
3. Digital voltmeter
4. Analog milli-ammeter, use on 0 - 10 mA range.
5. Computer and A/D interface
6. LabView program
7. Grating spectrometer

3.3 Precautions

Personnel
All of the equipment is low voltage except for the 120V line voltage when you plug in the power supply.

Apparatus
For the sake of both the diodes and the analog meter, avoid excessive currents. **The current through the diodes should not exceed 10 mA.** You should make sure that the over current protection on the power supply is set to 10mA. Check with the instructor if you are not sure how to set it.

3.4 Procedure

Part C: Photodiode determination of *h/e*

C.1. Install and run the LabView Program: The setup of the program is identical to that described in Section B.2 except that there is no zero current option.

C.2. Electrical Arrangement: Check that the circuit is wired correctly (refer to Fig. 7) before turning on any power. Make sure that the fuse is OK. Check with the instructor on how to operate the power supply, especially how to set the current limit. Note that there is only one lead to a single diode on the board that can be moved to select a particular diode.

C.3. Data Acqutition: For each diode obtain data on the diode current, I, versus the voltage across the diode, V, over a range of currents 0 to 10 mA. It is important to take as many data points near and above the turn-on potential. The reason for this is that the current through the diode rises exponentially for V>0:

$$I = I_S\left(e^{eV/kT} - 1\right) \quad \text{Eq. (6)}$$

Where I_S is the reverse biased saturation current. You do not have to average as many IV curves as you did in part B.2. I_S is a function of the diffusion potential V_D. Plotting Eq. (6) gives a curve like the one shown in Fig. 8. There is a "knee" in the curve where the current begins to increase rapidly. The applied voltage at the "knee" is proportional to the minimum emission voltage for light. From the discussion in Part III the voltage at the "knee" must be approximately V_D. Since we need V_D to apply Eq. (5), data below the turn on potential will not be used in the analysis. Repeat the IV curves for each diode 2-3 times to help get a handle on the errors in your measurements.

Notice that each LED (in the **visible** region) will begin to emit light when the voltage is above the knee in the IV curve. Again, this is because at this voltage you are injecting a significant amount of electrons into the depletion region where they recombine with holes and emit light. This observation indicates that the

two physical phenomena (light emission and conduction) are causally linked.

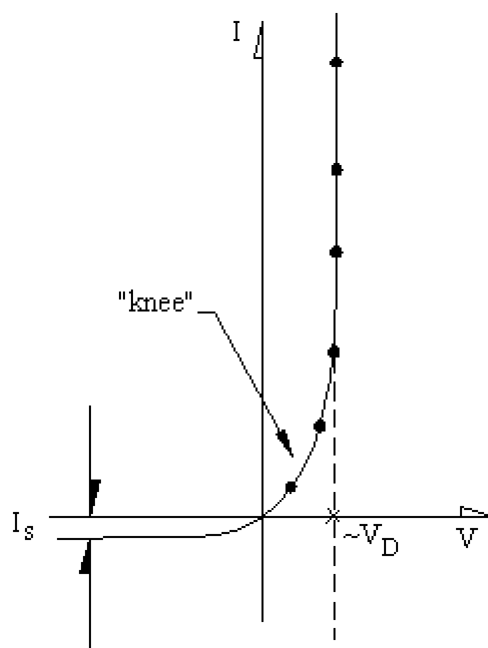


Figure 8. A typical "IV" curve for a p-n junction diode. The extrapolated diffusion potential is also shown.

C.4. Data Ananlysis:

C.4.1. Determing V_D: For each of the diode "IV" curves extrapolate the linear portion of the curve above the knee to its intercept with the voltage axis (see Fig. 8). This gives an approximate value for V_D. In your analysis you should look at how sensitive your value of V_D is to the range or number of points used in your extrapolation. This gives you an error measurement to your value of V_D. For you report plot all six IV curves on a single graph and show the best fit extrapolated V_D. You can also take derivative of the IV curves as well. This has particulr advantage. The derivative of Eq. (6) should also be an exponential. However, you will find that the highest voltages in the derivative IV curve do not follow a simple exponential. The derivative IV's therefore allow you to pick the part of the IV curve where the exponential approximation is good. Use this part of the data to do the extrapolation.

C.4.2. Determing *h/e*: For each diode plot your extrapolated values of V_D versus the frequency, ν, of the light emitted from the diode. The wavelength of the light from each diode is listed in the Table 1 below. From Eq. (5) the slope of the V_D vs. ν curve is *h/e*.

Table 1
Physical Properties of the LEDs

	Diode 1	Diode 2	Diode 3	Diode 4	Diode 5	Diode 6
Wavelength (nm)	950±20	665±15	635±15	590±15	560±15	480±40
Color	IR	Red	Super-Red	Yellow	Green	Blue
Composition	GaAs:Si	$GaAs_{.6}P_{.4}$:N	$GaAs_{.35}P_{.65}$:N	$GaAs_{.15}P_{.85}$:N	GaP:N	SiC

C.4.3. Errors and other considerations: Your report should also include some discussion of the physics of light emitting diodes. In particular you should consider the errors associated with the approximation given in Eq. (4). There is usually a spectral spread in the light emitted by the diode (see Fig. 9). Use the grating spectrometer to look at the wavelength distribution from each diode. You do not have to report exact numbers but you should qualitatively sketch the spectral

distribution for each diode. Why is there a spread and how does it influence the error in your determination of *h/e*?

Another source of error comes from the fact that the diffusion potential is a function of temperature. Investigation of the temperature dependence of V_D and comparison with reference data shows that V_D rises with falling temperature:

$$\frac{\Delta V_D}{V_{D,o}} \Delta T = -5.7x10^{-4} K \qquad \text{Eq. (7)}$$

Where ΔT and ΔV_D are the changes in temperature and diffusion potential, respectively, relative to their T = 0 K values. Also $V_{D,0}$ is the diffusion potential at T = 0 K. This increase can explain the systematic error found in measurements at room temperature. Check this out by using Eq. (7) to estimate $V_{D,0}$ and replotting $V_{D,0}$ vs. ν. Compare the values of *h/e* found from this plot to the one determined in Sec. C.3.2.

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