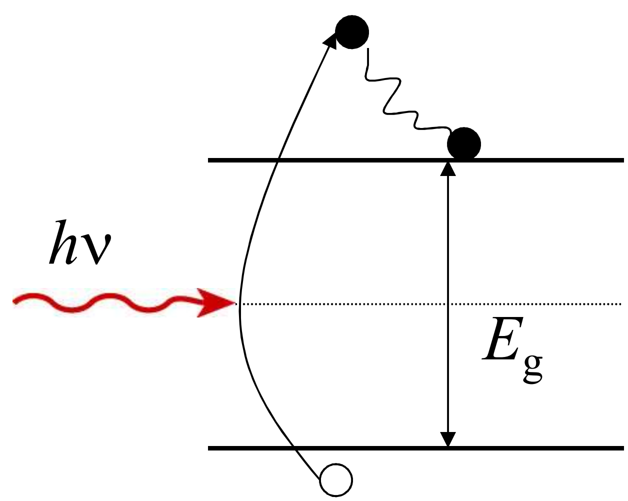
# Chapter 3-4. R-G statistics

- R-G statistics is the mathematical characterization of R-G processes
- An important generation process in device operation is **photo-generation**

If the photon energy ($h\nu$) is greater than the band gap energy, then the light will be absorbed thereby creating electron-hole pairs



# Photo-generation

The intensity of monochromatic light that passes through a material is given by: $I = I_0 \exp(-\alpha x)$ where $I_0$ is the light intensity *just* inside the material at $x = 0$, and $\alpha$ is the absorption coefficient. Note that $\alpha$ is material dependent and is a strong function of $\lambda$.

Since photo-generation creates equal #s of holes and electrons, and each photon creates one e-h pair, we can write:

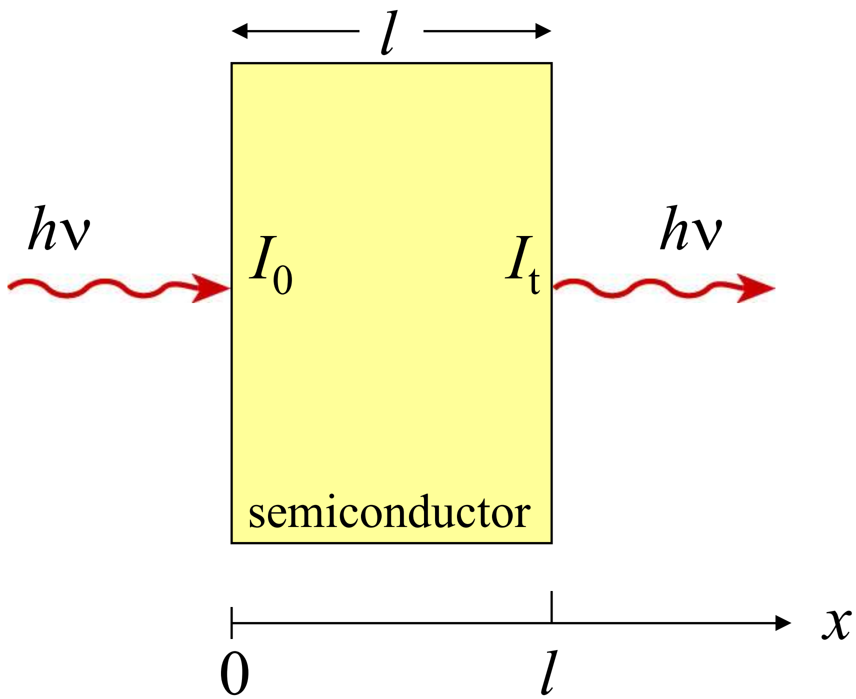
$$\frac{\partial n}{\partial t}\Big|_{\text{light}} = \frac{\partial p}{\partial t}\Big|_{\text{light}} = G_{\text{L}}(x,\lambda) = G_{\text{L}0}e^{-\alpha x}$$

where $G_{\text{L}0}$ is the photo-generation rate [# / (cm$^3$ s)] at $x = 0$

Question: What happens if the energy of photons is less than the band gap energy?

# Light absorption and transmittance

Consider a slab of semiconductor of thickness $l$.




$$I_t = I_0 \exp(-\alpha l)$$

where $I_0$ is light intensity at $x = 0$ and $I_t$ is light intensity at $x = l$.

# Absorption coefficient vs. wavelength in semiconductors

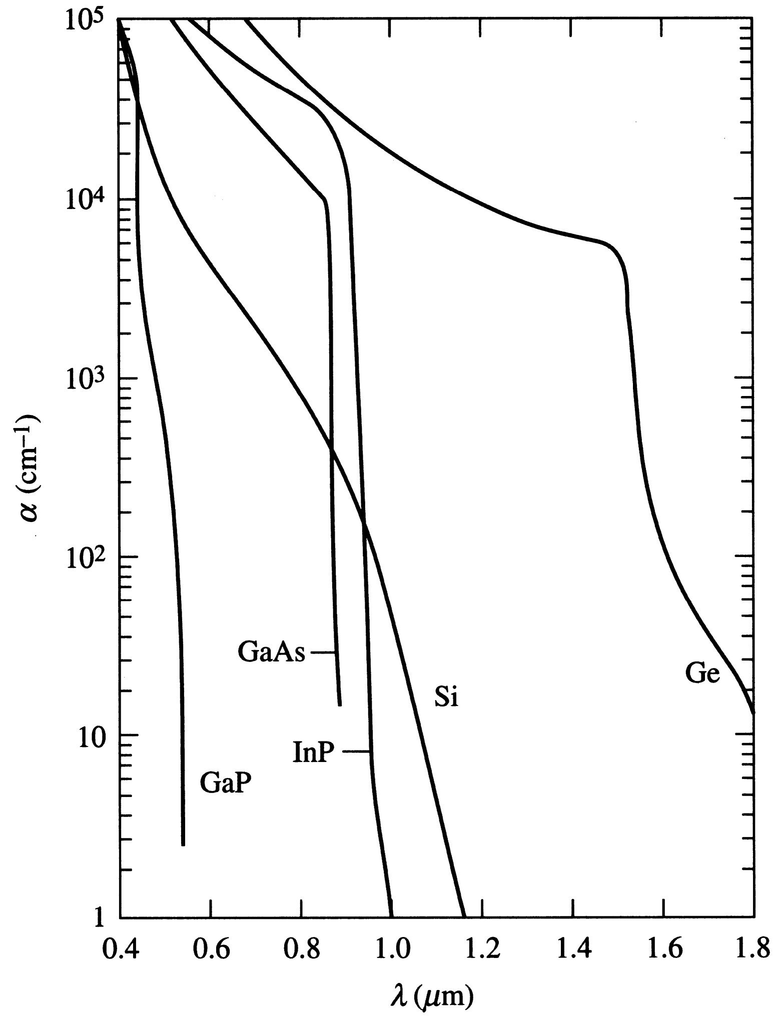
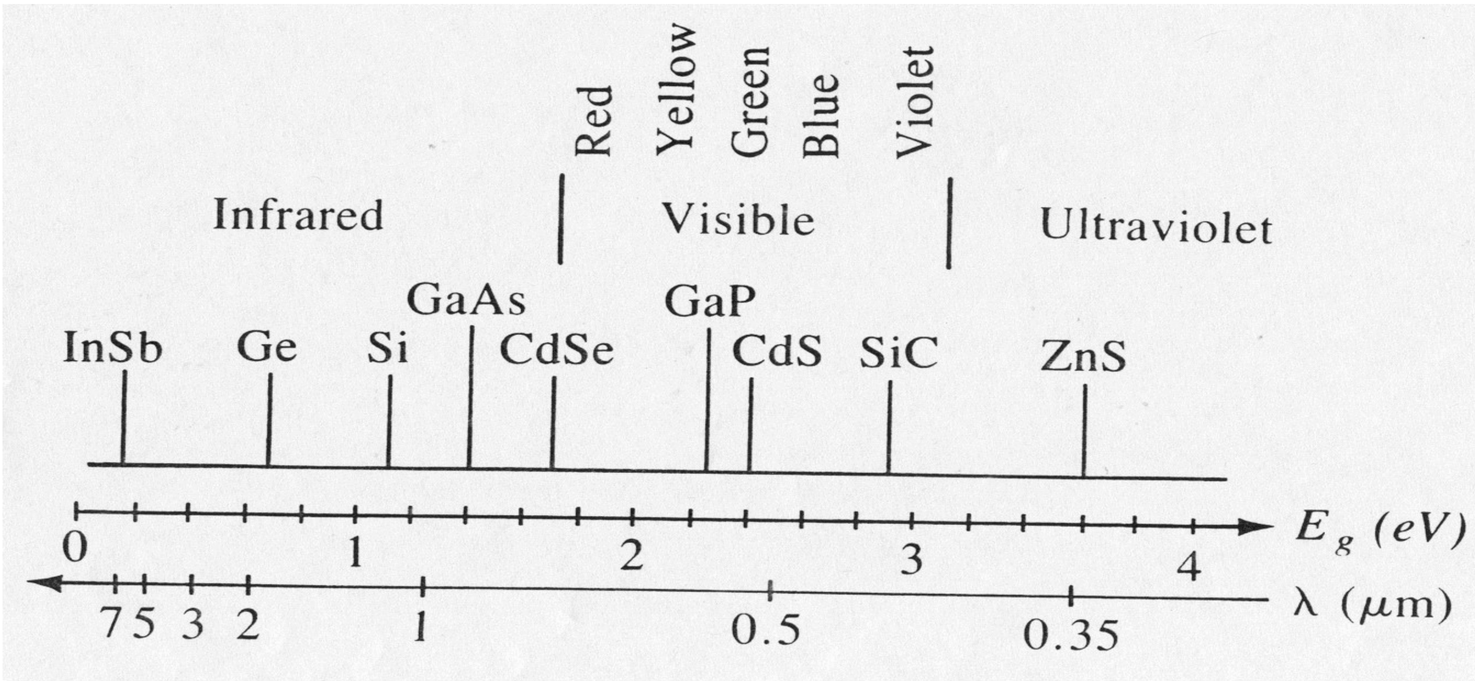



**Figure 3.20**

# Bandgaps of common semiconductors



# Indirect thermal recombination-generation

$n_0$, $p_0$ - under thermal equilibrium

$n$, $p$ - under arbitrary conditions, functions of $t$

$$\left.\begin{aligned} \Delta n &= n - n_0 \\ \Delta p &= p - p_0 \end{aligned}\right\}$$

$\Delta n$ and $\Delta p$ are deviations in carrier concentrations from their equilibrium values. $\Delta n$ and $\Delta p$ can be both positive or negative.

$N_t$ is the # of R-G centers/cm$^3$

**Low-level injection** condition is assumed.

– Change in the majority carrier concentration is negligible. For example, in n-type material, $\Delta p << n_0$ ; $n \approx n_0$.

# R-G statistics

Consider n-type silicon under perturbation:

We look at only minority carriers, and in this case, holes.

In general,

$$\frac{\partial p}{\partial t} = \left.\frac{\partial p}{\partial t}\right|_{\mathrm{R}} + \left.\frac{\partial p}{\partial t}\right|_{\mathrm{G}} + G_{\mathrm{L}}(x,\lambda)$$

| rate of hole build up | (loss) due to recomb. | (gain) due to generation | external such as light |
|---|---|---|---|

$\left.\frac{\partial p}{\partial t}\right|_{\mathrm{R}}$ should be proportional to $p$ and $N_{\mathrm{t}}$. Why?

$$\left.\frac{\partial p}{\partial t}\right|_{\mathrm{R}} = -C_{\mathrm{p}} N_t \, p$$

# R-G statistics (continued)

Under thermal equilibrium, $G_L = 0$; and $dp/dt = 0$

$$\longrightarrow \quad \frac{\partial p}{\partial t}\Big|_G = -\frac{\partial p}{\partial t}\Big|_R = C_p N_t p_0$$

So, under arbitrary conditions, when $G_L = 0$,

$$\frac{\partial p}{\partial t} = -C_p N_t p + C_p N_t p_0$$

$$= -\frac{\Delta p}{\tau_p} \qquad \text{defining} \quad \tau_p = \frac{1}{C_p N_t}$$

Since $\displaystyle \frac{\partial p}{\partial t} = \frac{\partial}{\partial t}\left(p_0 + \Delta p\right) = \frac{\partial \Delta p}{\partial t}$

# R-G statistics (continued)

We can write:

$$\boxed{\frac{\partial \Delta p}{\partial t} = -\frac{\Delta p}{\tau_P}}$$

For holes in n-type

Similarly,

$$\boxed{\frac{\partial \Delta n}{\partial t} = -\frac{\Delta n}{\tau_n}}$$

For electrons in p-type

$\tau_p$ (or $\tau_n$) is called "**minority carrier lifetime**" indicating the average time an excess minority carrier will survive in a sea of majority carriers.

Minority carrier lifetime is an important material parameter. Depends strongly on the concentration of deep-level of impurities, crystalline quality etc.. Varies strongly from material to material. Varies from a few ns to few ms in silicon depending on the quality!

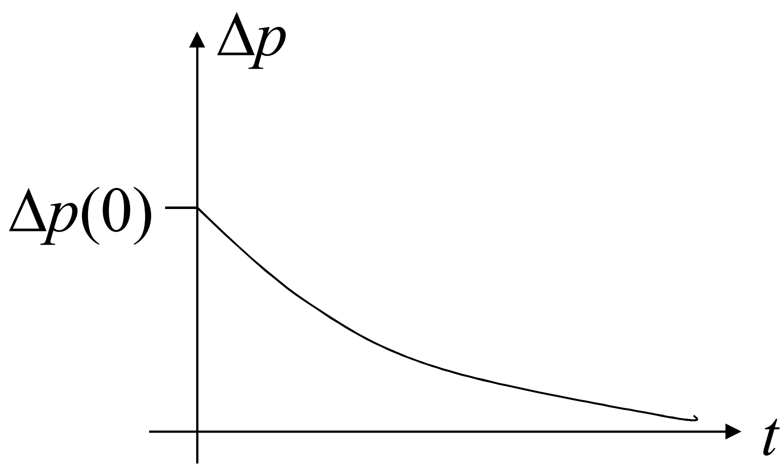
# What happens when the perturbation is removed at $t = 0$?

$$\boxed{\frac{\partial \Delta p}{\partial t} = -\frac{\Delta p}{\tau_p}}$$

For holes in an n-type semiconductor

The solution for $t > 0$ is:

$$\Delta p = \Delta p(0) \exp(-t / \tau_p)$$




The excess carrier concentration exponentially decays to zero when the external perturbation is removed. This fact is used to measure lifetimes using photo-conductivity decay technique. See Sect. 3.3.4.

# Photoconductivity decay measurement

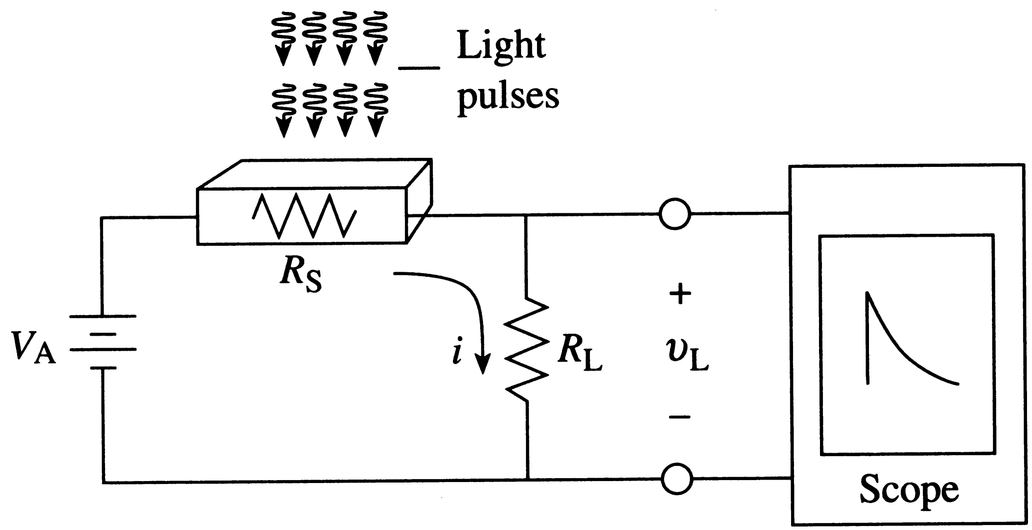



**Figure 3.22**

# Photoconductivity decay measurement system

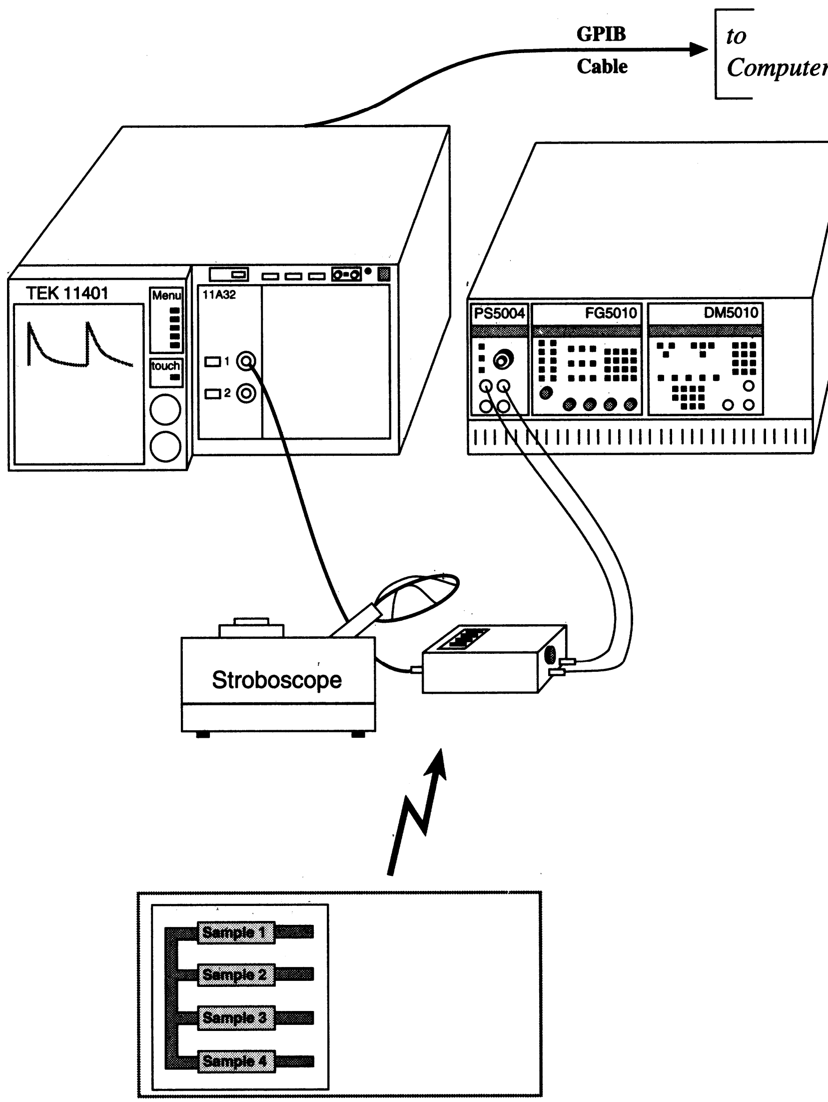



Figure 3.23

# Photoconductivity transient response

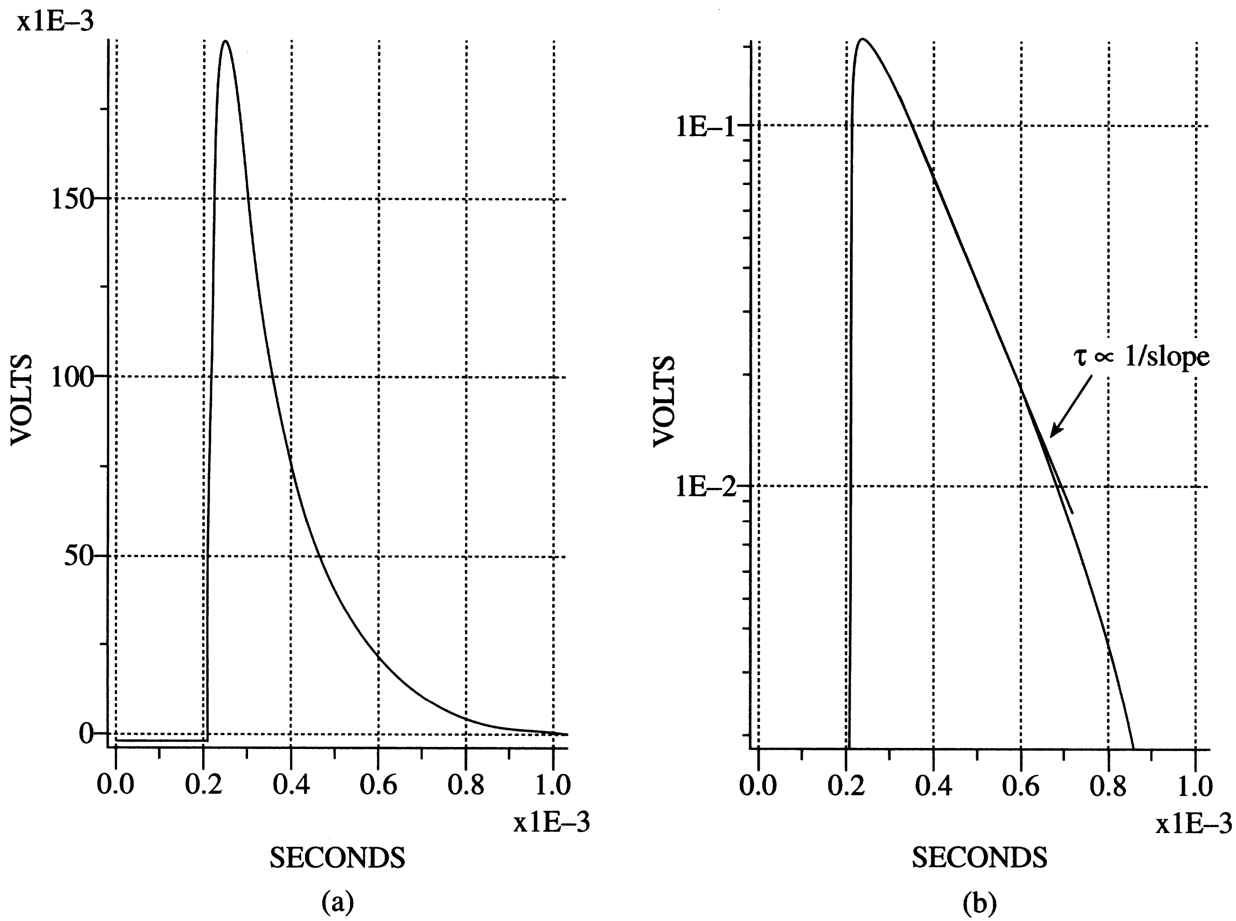



**Figure 3.24**