ECE 340 Lecture 14
Semiconductor Electronics

Spring 2022
10:00-10:50am

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Today's Discussion

- **Summary of previous lecture:**
  - **Optical absorption**
  - **Direct Recombination of Electrons and Holes**
- **Steady State Carrier Generation**
- **Photoconductive Devices**

Quick Recap

We have introduced the following optical processes in a semiconductor material:

1. **Absorption of light as a function of space**

2. **Recombination process after a uniform distribution of excess carriers has been generated (and the illumination is abruptly interrupted)**

Today we will discuss a third process:

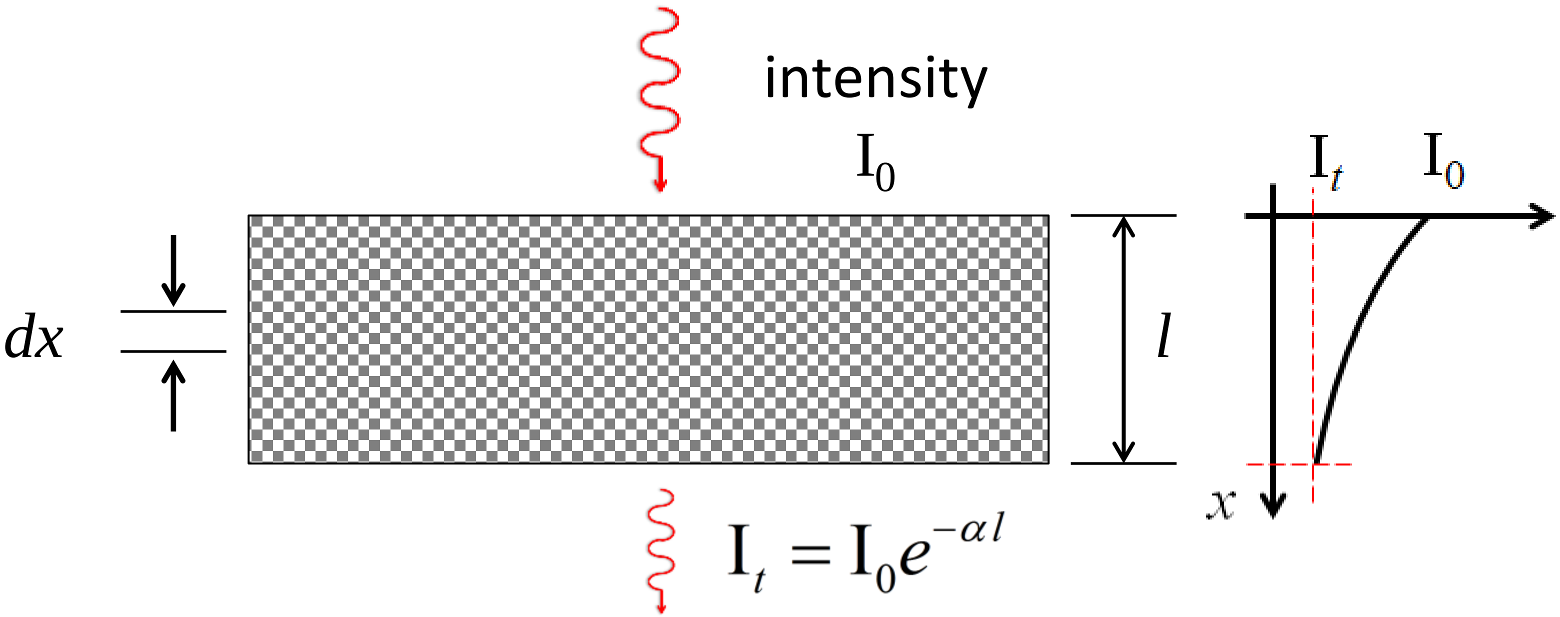
3. **Steady-state generation of excess carriers under continuous illumination**

1. Optical Absorption

I_0 [photons/cm^2-s]

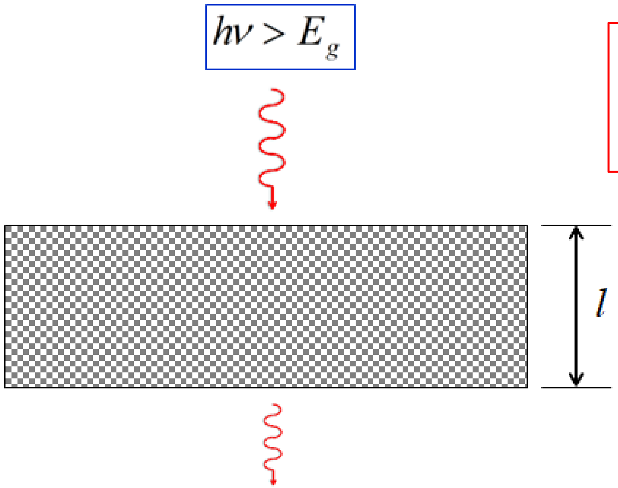
α = absorption coefficient

$\boxed{h\nu > E_g}$



$$-\frac{d\,I(x)}{dx} = \alpha\,I(x) \quad \Rightarrow \quad I(x) = I_0 e^{-\alpha x}$$

2. Recombination of Electrons and Holes



Now we pump electrons into the conduction band by a short flash of light that ends at *t = 0*

initial condition

$t = 0$

$\Delta n = \Delta p =$ initial excess concentration

$\delta n(t) =$ instantaneous concentration of excess electrons

$\delta p(t) =$ instantaneous concentration of excess holes

assumption $\quad \delta n(t) = \delta p(t)$

We have obtained the evolution equation

$$\frac{d\,\delta n(t)}{dt} = -\alpha_r\left[(n_o + p_o)\,\delta n(t) + \delta n^2(t)\right]$$

2. Recombination of Electrons and Holes

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r \left[(n_o + p_o)\,\delta n(t) + \cancel{\delta n^2(t)} \right]$$

Last term can be neglected in the case of "low level injection"

$$\delta n^2(t) \ll \left(n_o + p_0\right)\delta n(t)$$

$$\delta n(t) \ll \left(n_o + p_0\right)$$

In extrinsic semiconductor, we can predict the decay of minority carrier concentration due to recombination.

Low-level injection conditions → Simplification

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r \left[(n_o + p_o)\,\delta n(t) + \underbrace{\delta n^2(t)}_{\text{can be neglected}} \right]$$

Extrinsic semiconductor *p*-type

$$\frac{d\,\delta n(t)}{d\,t} \simeq -\alpha_r\, p_o\, \delta n(t) \qquad p_o \gg n_o$$

Neglect equilibrium minority carriers

$$\boxed{\delta n(t) = \underbrace{\Delta n}_{\substack{\text{initial}\\ \text{condition}}} \exp\left(-\alpha_r\, p_o\, t\right) = \Delta n \exp\left(-\frac{t}{\tau_n}\right)}$$

$$\tau_n = \frac{1}{\alpha_r\, p_o} = \text{minority recombination lifetime}$$

Low-level injection conditions → Simplification

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r \left[(n_o + p_o)\,\delta n(t) + \underbrace{\delta n^2(t)}_{\text{can be neglected}} \right]$$

Extrinsic semiconductor *n*-type

$$\frac{d\,\delta p(t)}{d\,t} \simeq -\alpha_r\, n_o\, \delta p(t) \qquad n_o \gg p_o$$

Neglect equilibrium minority carriers

$$\boxed{\delta p(t) = \underbrace{\Delta p}_{\substack{\text{initial}\\ \text{condition}}} \exp\left(-\alpha_r\, n_o\, t\right) = \Delta p \exp\left(-\frac{t}{\tau_p}\right)}$$

$$\tau_p = \frac{1}{\alpha_r\, n_o} = \text{minority recombination lifetime}$$

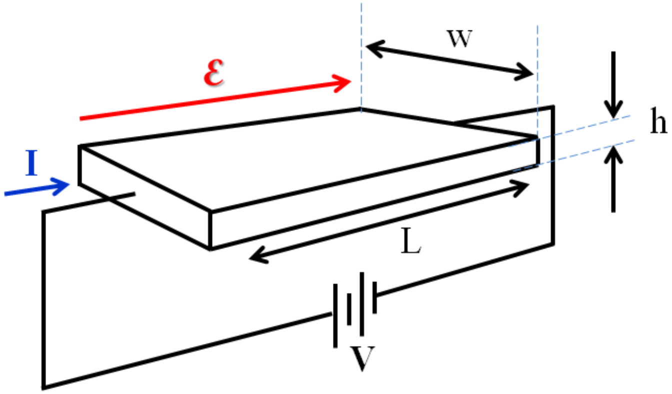
Low level injection conditions → Simplification

More generally you can use this formula

$$\tau = \frac{1}{\alpha_r \left(n_o + p_0\right)}$$

It works for both *p*- and *n*-type material in low level injection conditions

Remember this problem?



- **Resistivity**

$$\rho = \frac{1}{q\mu_n n_i + q\mu_p n_i} = \frac{1}{qn_i\left(\mu_n + \mu_p\right)} =$$

$$= \frac{1}{1.6\times10^{-19}\times1.5\times10^{10}\left(1350+480\right)} = 227.4\ \mathrm{k\Omega\cdot cm}$$

$$R = \rho\frac{L}{A} = 227.4\times10^{3}\,\frac{1.0}{10^{-2}} = 22.74\times10^{6} = 22.74\ \mathrm{M\Omega}$$

$$I = \frac{V}{R} = \frac{10}{22.74\times10^{6}} = 0.44\,\mu\mathrm{A}$$

Can we increase the current somehow (i.e. increase carrier concentration)?

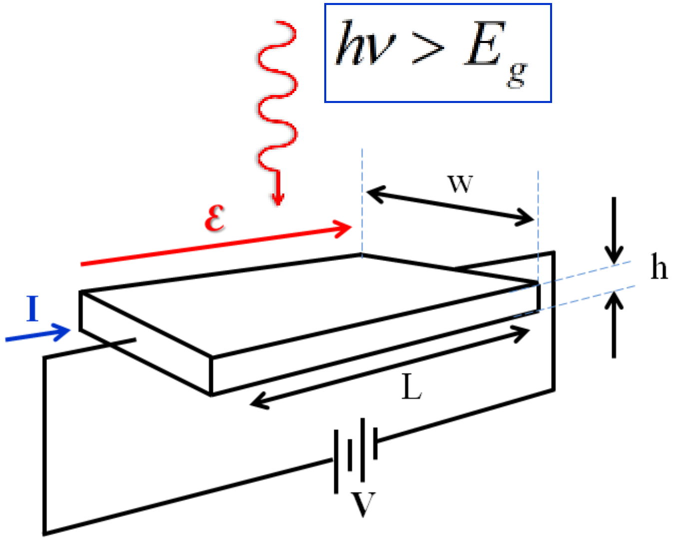
Assume photogeneration of 10^{16} cm^{-3}

$$\rho = \frac{1}{q\mu_n n_o + q\mu_p p_o} = \frac{1}{q n_o (\mu_n + \mu_p)} =$$

$$= \frac{1}{1.6\times10^{-19}\times10^{16}(1350+480)} = 0.34\,\Omega\cdot\mathrm{cm}$$

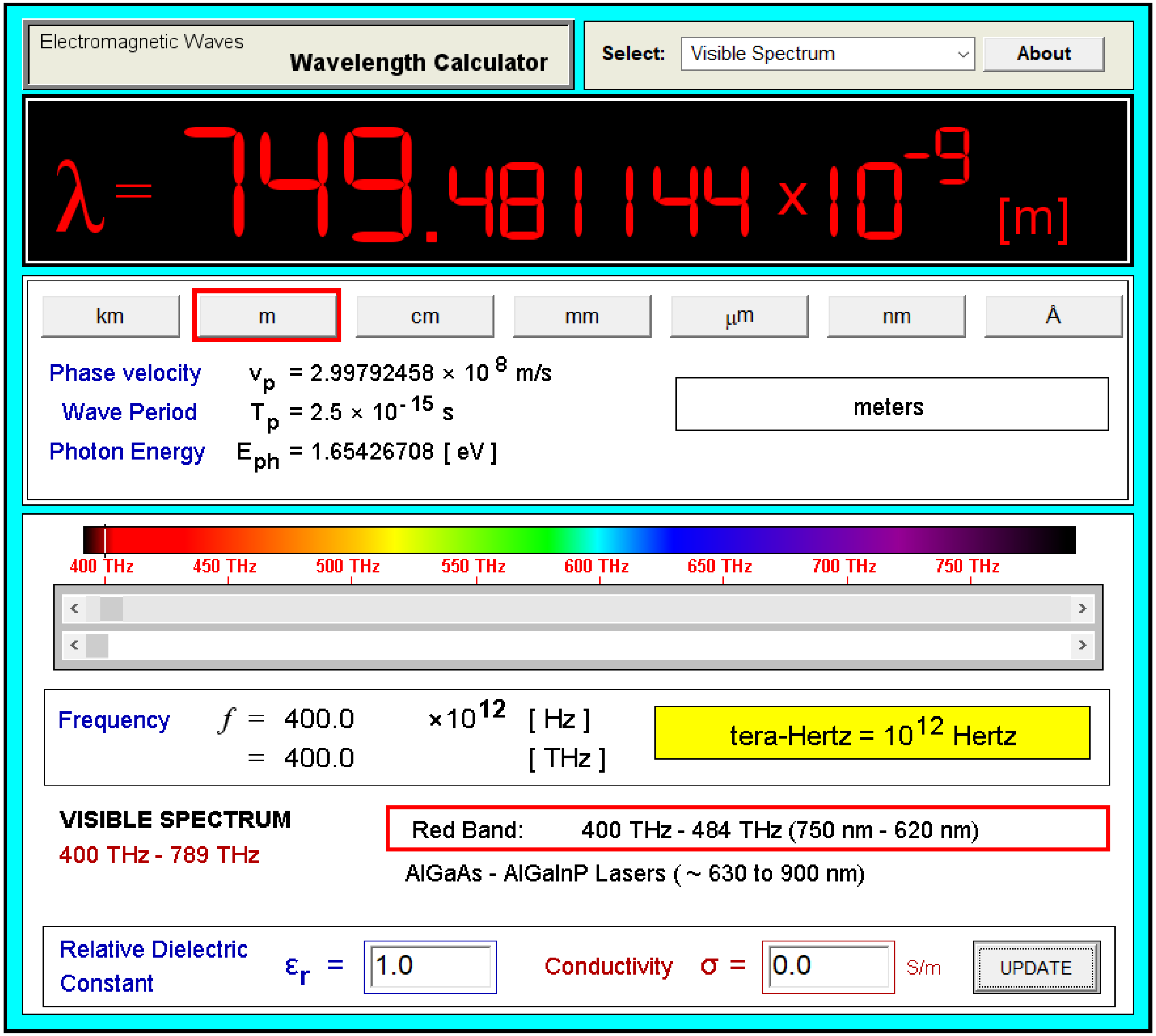
$$R = \rho\frac{L}{A} = 0.34\frac{1.0}{10^{-2}} = 34\,\Omega$$

$$I = \frac{V}{R} = \frac{10}{34} = 294\,\mathrm{mA}$$



Current has increased ~ 600,000 times. What uses could have this device?

To explore more the EM spectrum, download this desktop Java App



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Steady State Carrier Generation

- **After analyzing the transient decay of an excess electron-hole pair (EHP) population, we now look at the steady-state regime.**

Again, we give another look at thermal equilibrium.

At any temperature T there is a thermal generation rate

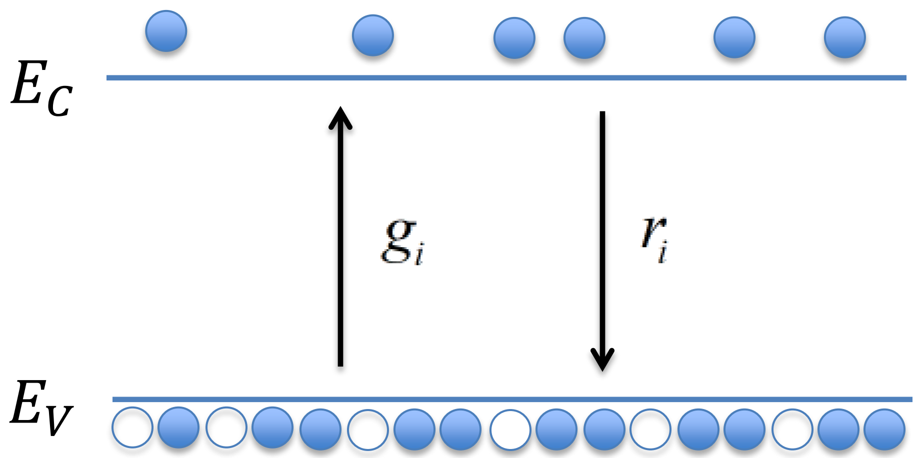
$$g(T) = g_i$$

Steady-state thermal equilibrium

Thermal recombination rate = thermal generation rate

$$r_i = \alpha_r n_o p_o = \alpha_r n_i^2 = g_i$$

with α_r a proportionality constant.



Steady-state generation of excess EHP

Total generation rate

$$\underbrace{g(T)}_{\text{thermal generation}} + \underbrace{g_{op}}_{\text{optical generation}} = \alpha_r\, n\, p = \alpha_r\,(\underbrace{n_o}_{\text{thermal equilibrium}} + \underbrace{\delta n}_{\text{excess generation}})(\underbrace{p_0}_{\text{thermal equilibrium}} + \underbrace{\delta p}_{\text{excess generation}})$$

Steady state (and no trapping)

$$\delta n = \delta p$$

Low-level excitation

$$\cancel{\underbrace{g(T)}_{\text{thermal generation}}} + g_{op} = \cancel{\underbrace{\alpha_r\, n_o\, p_o}_{\text{thermal generation}}} + \alpha_r\left[\left(n_o + p_0\right)\delta n + \cancel{\underbrace{\delta n^2}_{\text{neglect}}}\right]$$

$$\boxed{g_{op} = \alpha_r\left(n_o + p_0\right)\delta n = \frac{\delta n}{\tau_n}}$$

$$\tau_n = \tau_p = \frac{1}{\alpha_r\left(n_o + p_0\right)}$$

Steady-state generation of excess EHP

$$g_{op} = \alpha_r (n_o + p_0)\delta n = \frac{\delta n}{\tau_n}$$

Steady-state excess carrier concentration

$$\boxed{\delta n = \delta p = g_{op}\, \tau_n}$$

If $\tau_n \neq \tau_p$ (e.g., recombination via traps)

$$\delta n = g_{op}\, \tau_n$$

$$\delta p = g_{op}\, \tau_p$$

Photoconductive Devices

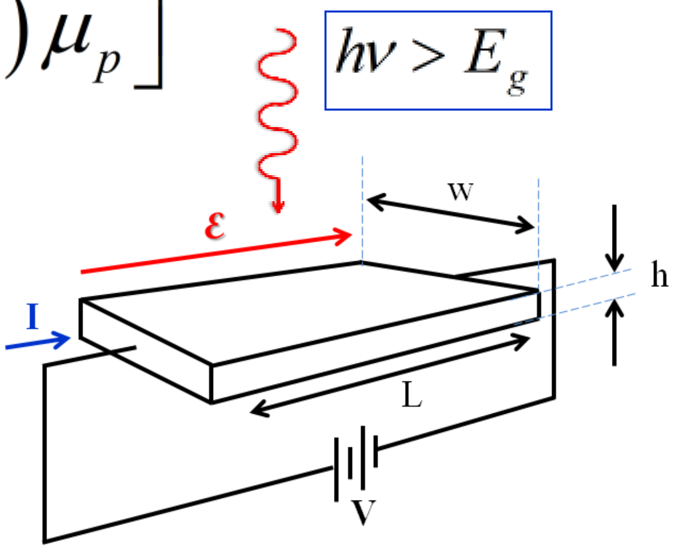
- Conductivity before illumination

$$\sigma = \sigma_n + \sigma_p = q\left(n\mu_n + p\mu_p\right)$$

- After illumination, change in conductivity

$$\sigma + \Delta\sigma = q\left[\left(n + \delta n\right)\mu_n + \left(p + \delta p\right)\mu_p\right]$$

$$\Delta\sigma = q\left[\delta n \mu_n + \delta p \mu_p\right]$$



Photoconductive Devices

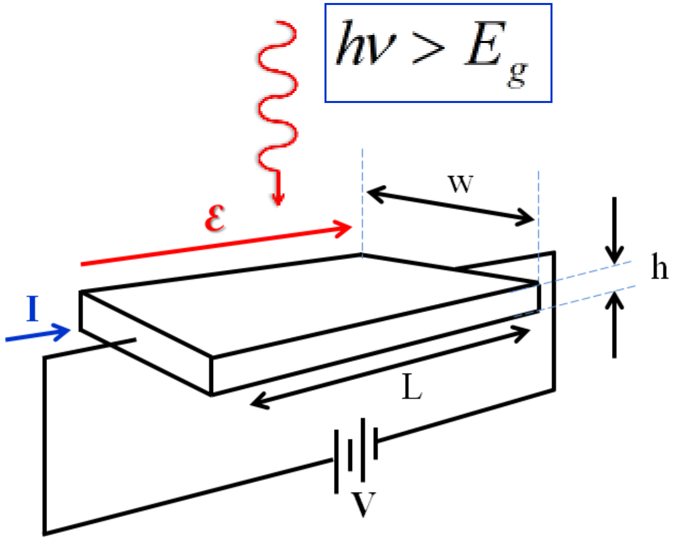
$$\Delta\sigma = q\left[\delta n \mu_n + \delta p \mu_p\right]$$

$$\delta n = g_{op}\,\tau_n$$

$$\delta p = g_{op}\,\tau_p$$

$$\boxed{\Delta\sigma = q\, g_{op}\left(\tau_n \mu_n + \tau_p \mu_p\right)}$$

- For high sensitivity
  - High mobility
  - Long recombination times



Some Photoconductive Materials

			E_g (eV)	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm^3)	Melting point (°C)
	Si	(i/D)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
IR	Ge	(i/D)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
	SiC (α)	(i/W)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
	AlP	(i/Z)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
	AlAs	(i/Z)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
	AlSb	(i/Z)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
	GaP	(i/Z)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
	GaAs	(d/Z)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
	GaN	(d/Z, W)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
	GaSb	(d/Z)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
	InP	(d/Z)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
	InAs	(d/Z)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
IR	InSb	(d/Z)	0.18	10^5	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
	ZnS	(d/Z, W)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
	ZnSe	(d/Z)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
	ZnTe	(d/Z)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
VIS	CdS	(d/W, Z)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
	CdSe	(d/W)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
	CdTe	(d/Z)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
	PbS	(i/H)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
	PbSe	(i/H)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
	PbTe	(i/H)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

All values at 300 K.

*Vaporizes

Example

- Consider Si at T=300K and $n_o = 10^{14}\mathrm{cm}^{-3}$

- Optical generation $10^{19}\mathrm{EHP\ cm}^{-3}/\mathrm{s}$
- Recombination lifetimes

$$\tau_n = \tau_p = 2 \times 10^{-6}\mathrm{s}$$

- Steady-state concentration

$$\delta n = \delta p = g_{op}\tau_n =$$
$$= 10^{19} \times 2 \times 10^{-6} = 2 \times 10^{13}\mathrm{cm}^{-3}$$

Example

- Holes equilibrium concentration

$$p_o = \frac{n_i^2}{n_o} = \frac{2.25 \times 10^{20}}{10^{14}} = 2.25 \times 10^6 \mathrm{cm}^{-3}$$

- Holes total concentration

$$p_o + \delta p = 2.25 \times 10^6 + 2 \times 10^{13} \approx 2 \times 10^{13} \mathrm{cm}^{-3}$$

- Electrons total concentration

$$n_o + \delta n = 10^{14} + 2 \times 10^{13} = 1.2 \times 10^{14} \mathrm{cm}^{-3}$$

$$n_o p_o = n_i^2$$

$$\Rightarrow \quad np \neq n_i^2$$

Example

- Quasi-Fermi level for electrons

$$n_o + \delta n = n = 1.2 \times 10^{14}\mathrm{cm}^{-3}$$

$$n = n_i \exp\left[\frac{F_n - E_i}{k_B T}\right]$$

$$0.0259 \times \ln\frac{1.2 \times 10^{14}}{1.5 \times 10^{10}} = F_n - E_i$$

$$F_n - E_i = 0.0259 \times \ln(8 \times 10^3) = 0.233\mathrm{eV}$$

Example

- Quasi-Fermi level for holes

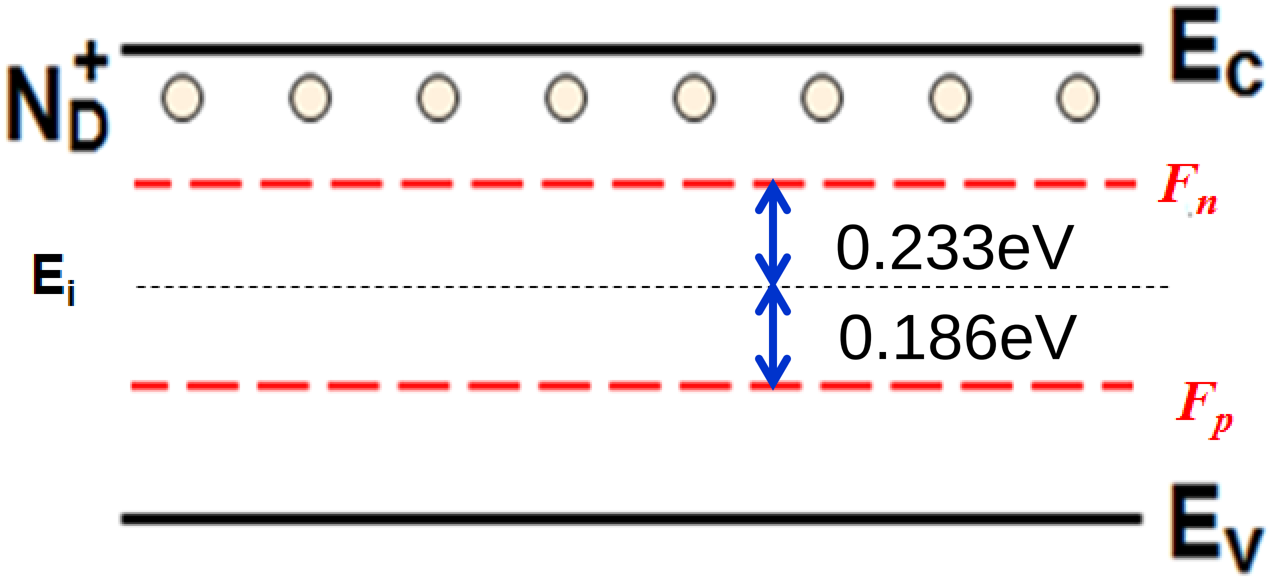
$$p_o + \delta p = p = 2 \times 10^{13} \mathrm{cm}^{-3}$$

$$p = n_i \exp\left[\frac{E_i - F_p}{k_B T}\right]$$

$$0.0259 \times \ln \frac{2 \times 10^{13}}{1.5 \times 10^{10}} = F_p - E_i$$

$$E_i - F_p = 0.0259 \times \ln(1.\overline{3} \times 10^3) = 0.1864\ \mathrm{eV}$$

Example



$$n = n_i e^{(F_n - E_i)/kT}$$

$$p = n_i e^{(E_i - F_p)/kT}$$