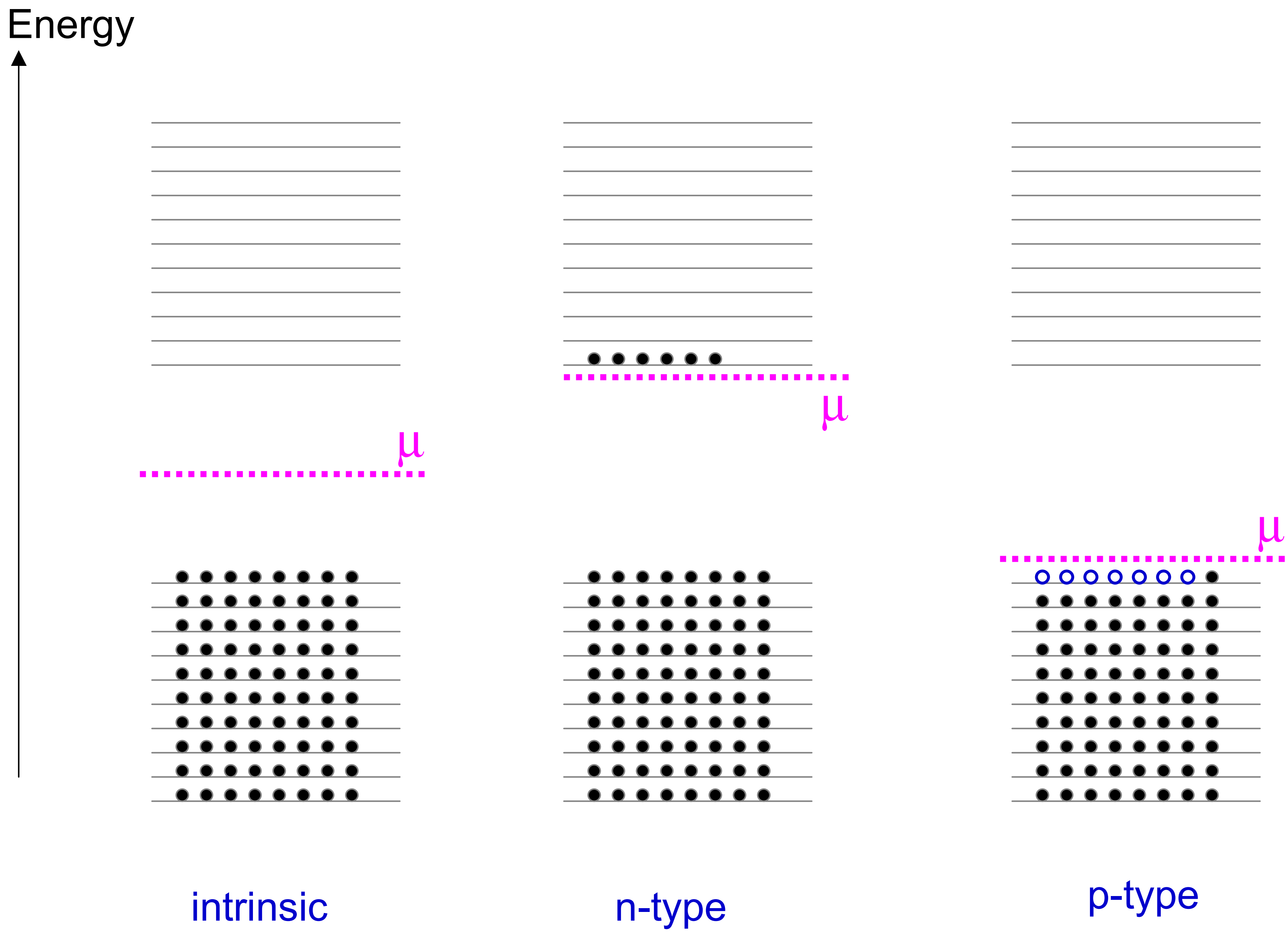
From Lec 20: Chemical potential of radiation

- μ constant in semiconductor at equilibrium
- Photogeneration causes increase in *n*, *p* over equilibrium values
- Define

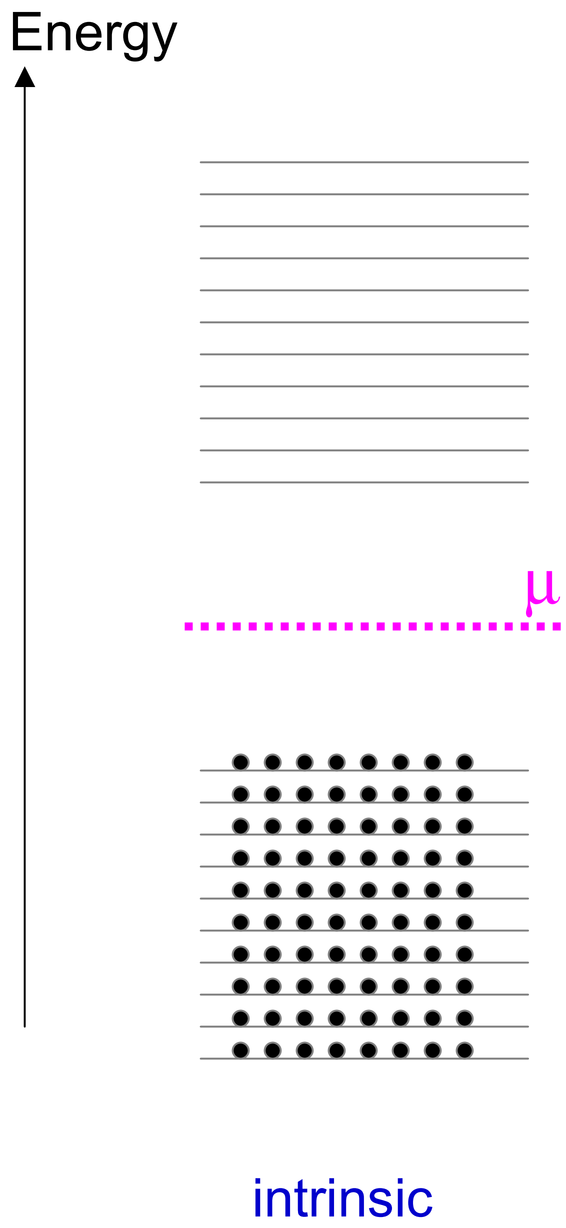
$$n = n_C e^{-(E_C - \mu_n)/kT}$$

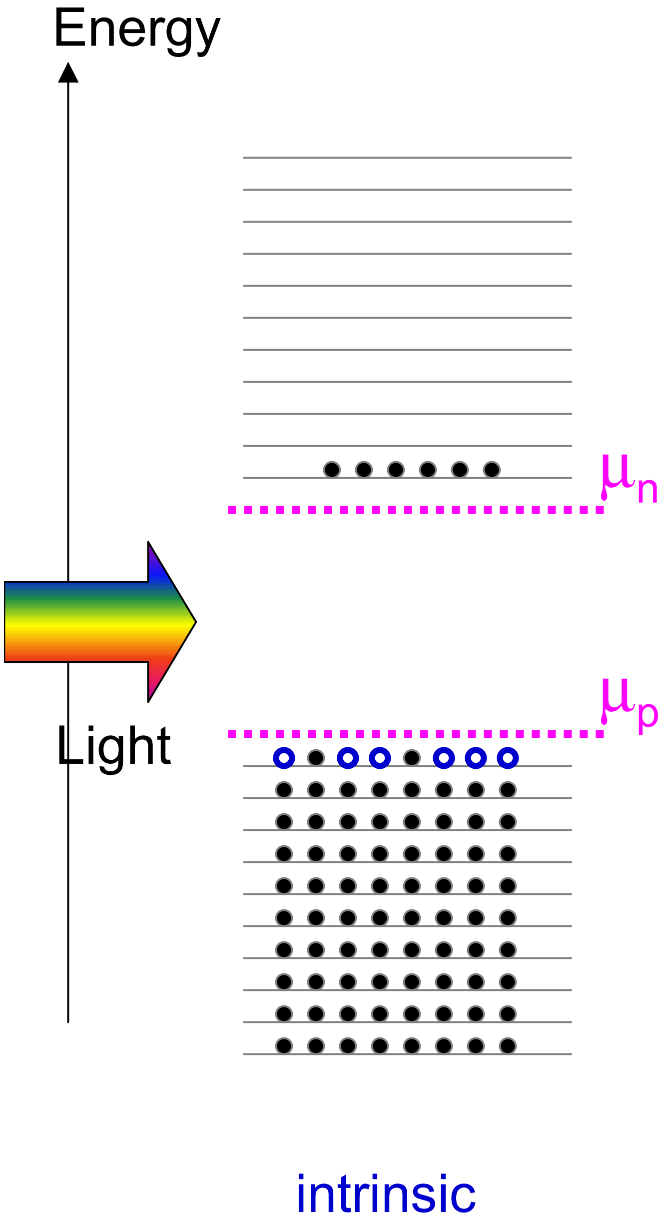
$$p = n_V e^{-(\mu_p - E_V)/kT}$$

- Photogeneration causes $\mu_n > \mu_p$
- $\Delta\mu = \mu_n - \mu_p$ available for electric work.

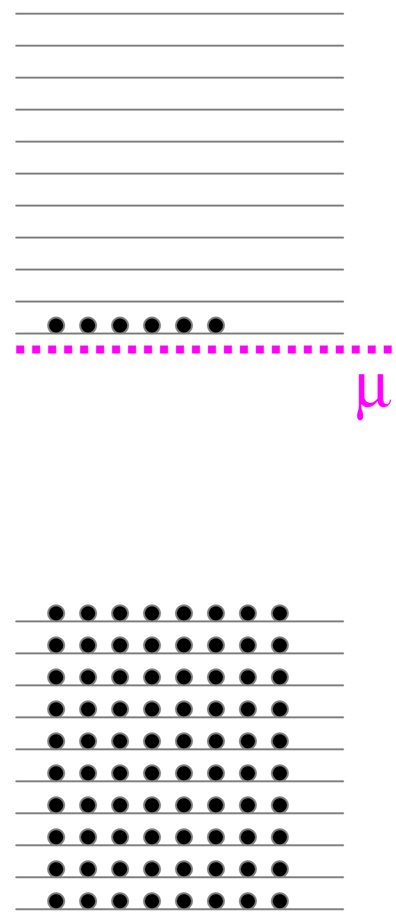


Energy
μ
μ
μ
intrinsic
n-type
p-type

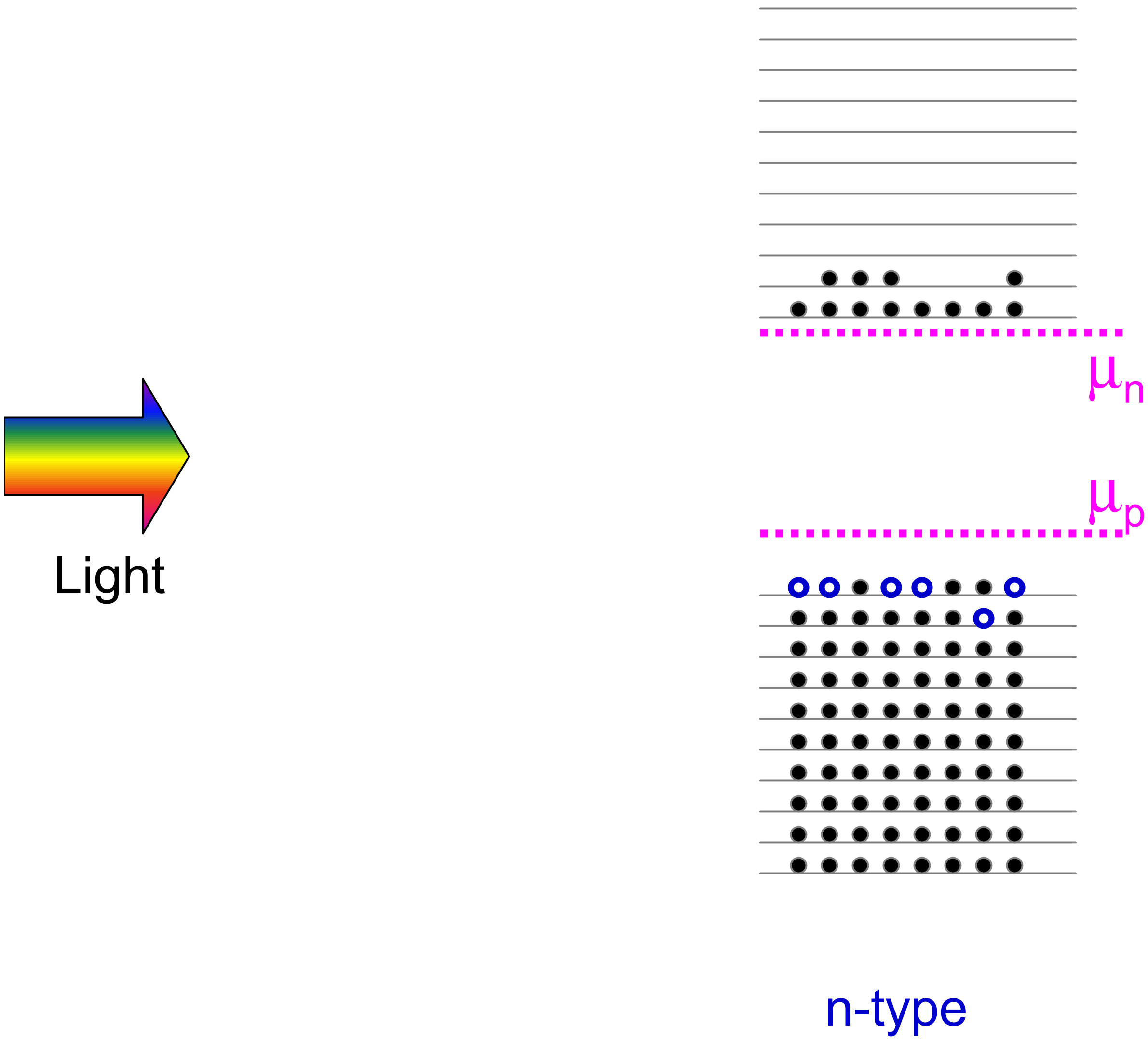

Energy
μ
intrinsic

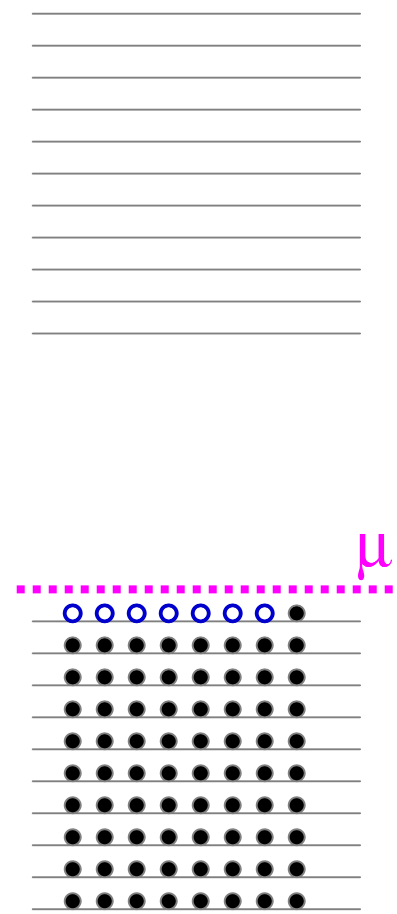


Energy
μn
μp
Light
intrinsic

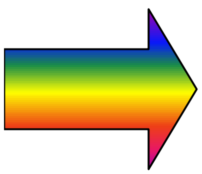


n-type

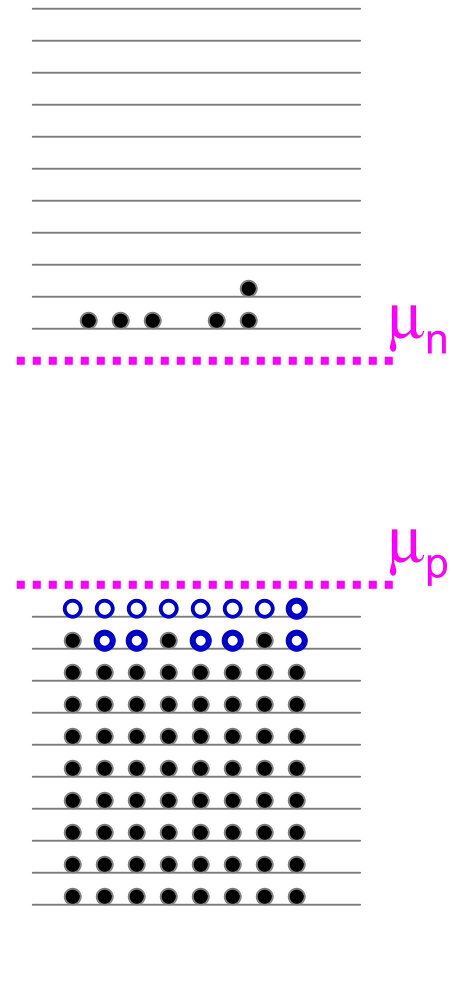

μ_n
μ_p
Light
n-type



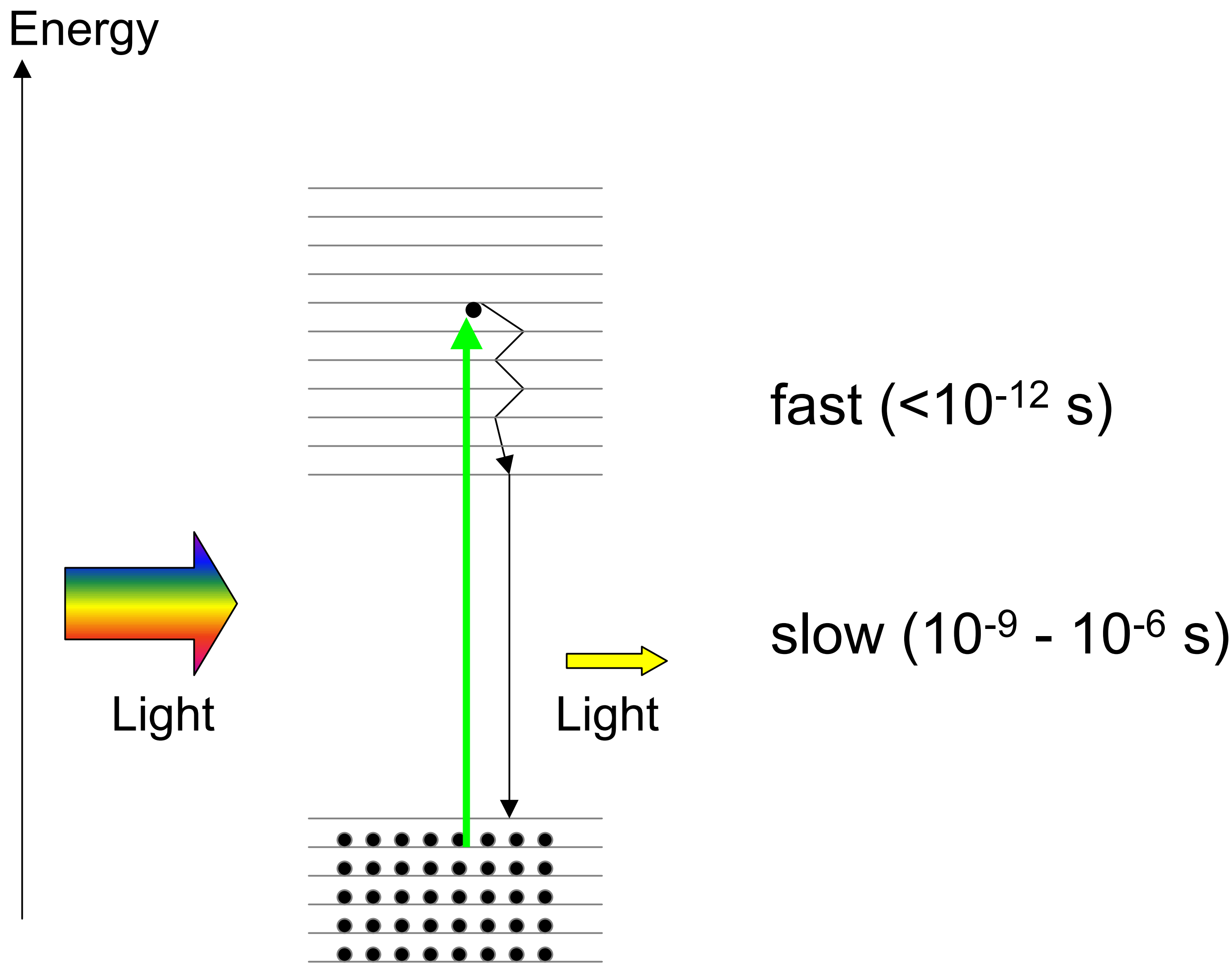
p-type



Light



p-type

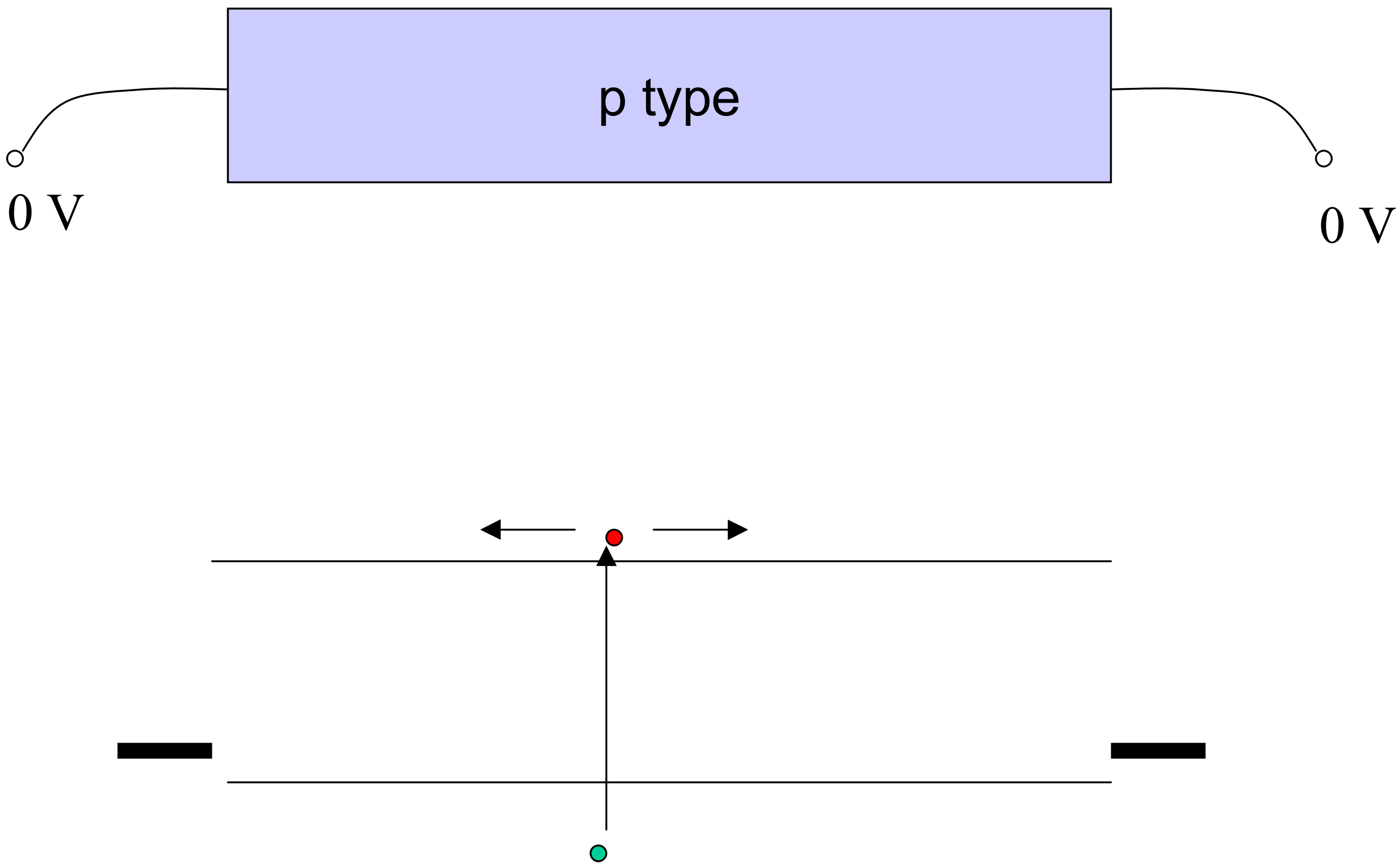

Energy
Light
Light
fast (<10^-12 s)
slow (10^-9 - 10^-6 s)

Summary of Lecture 20

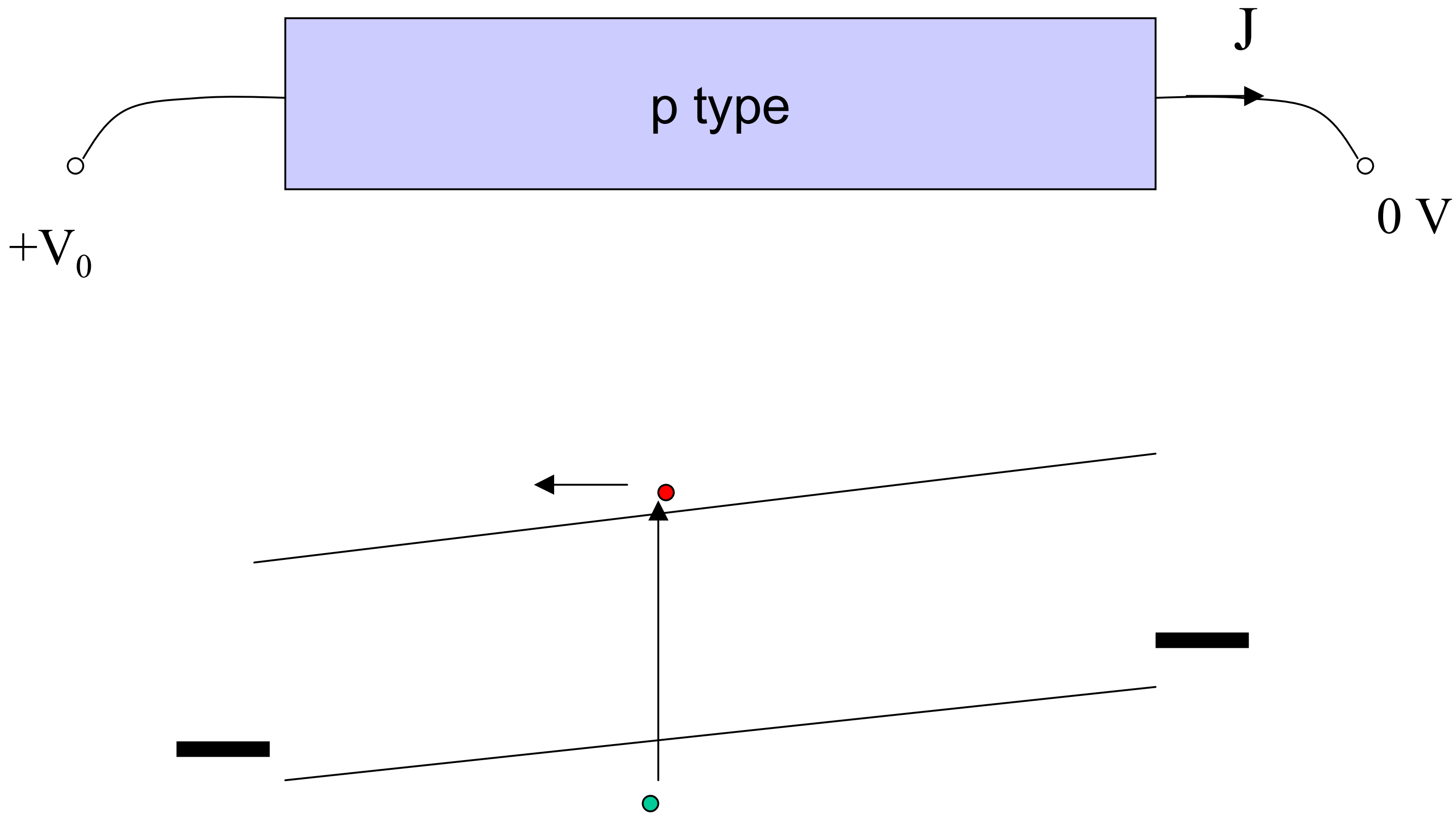
- Semiconductor has
  - electron density $n = n_C \exp(-(E_C-\mu_n)/kT)$
  - hole density $p = n_V \exp(-(\mu_p - E_V)/kT)$
- Doping changes μ and n/p ratio
- μ constant in equilibrium
- Photogeneration causes $\mu_n > \mu_p$
- For electrons in p-type semiconductor:
  - Photogeneration rate $G = \int \alpha\, b\, dE$
  - Recombination rate $R = n / t_n$
  - Diffusion current $J_n = e D_n\, dn/dx$
  - Continuity equation $\frac{1}{e}\frac{dJ_n}{dx} + G - R = 0$

- To generate electric power from solar radiation we need
  - An energy gap (to keep photo-generated electrons at high $\Delta\mu$)
  - A preferred direction for electron extraction

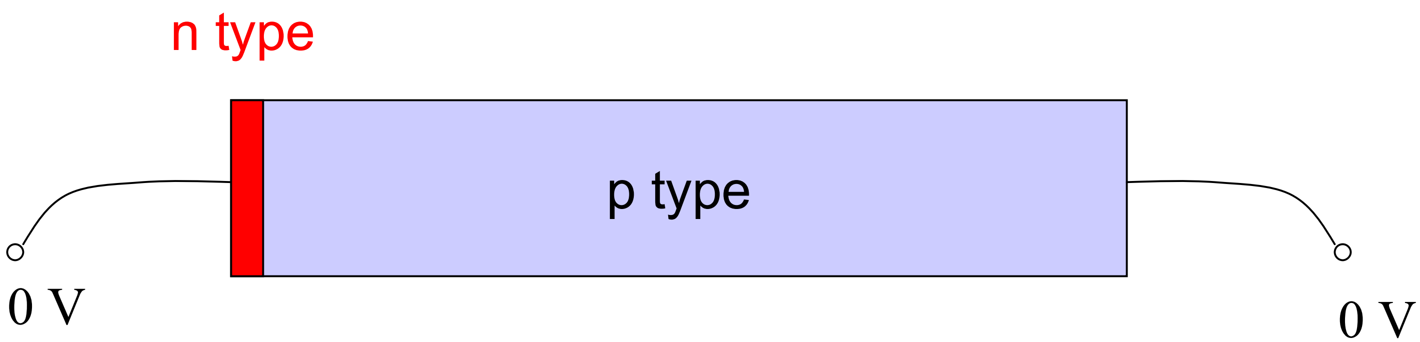
- A semiconductor provides the energy gap
- ...

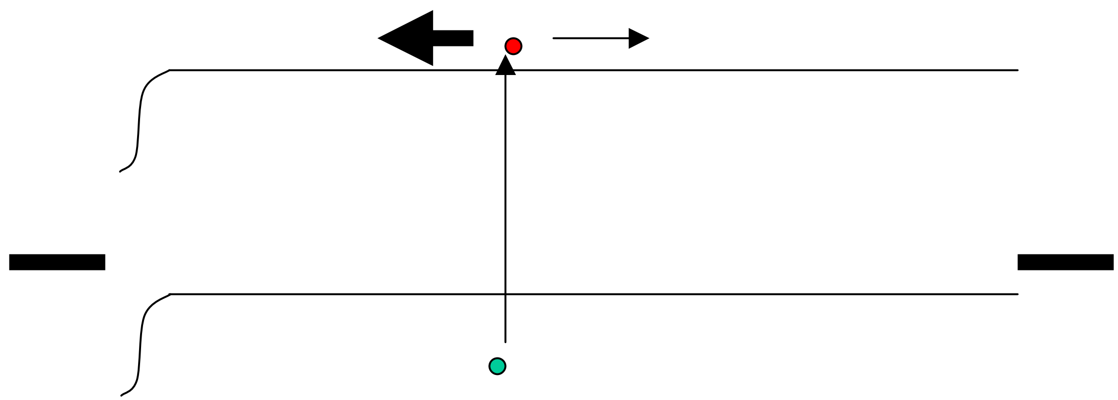


No driving force to direct photocurrent

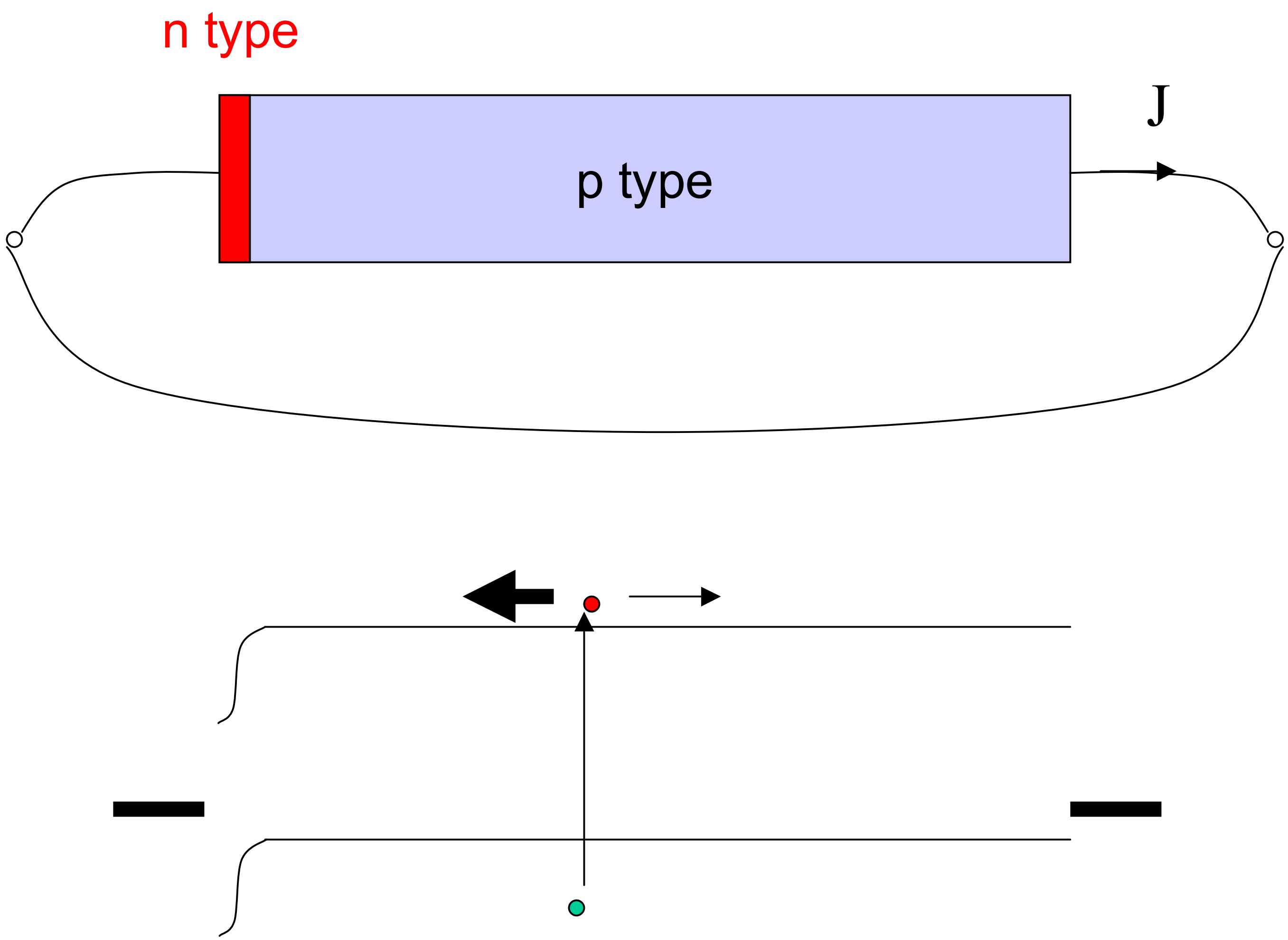


Applied voltage drives photocurrent, but power consumed





Compositional change drives photocurrent



Compositional change drives photocurrent

- To generate electric power from solar radiation we need
  - An energy gap (to keep photo-generated electrons at high $\Delta\mu$)
  - A preferred direction for electron extraction

- A semiconductor provides the energy gap
- Asymmetric contacts (for directed charge extraction) can be provided by a p-n or n-p junction

Continuity equation for electrons $$\frac{1}{e}\frac{dJ_n}{dx}+G-R=0$$

Boundary conditions: $n(0)=0$ $J_n(d)=0$

Use definitions of R and J_n (diffusion) $$D_n\frac{d^2n}{dx}-\frac{n}{t_n}=-G$$

Second order inhomogeneous DE

Solution = complementary function + particular integral

CF: $n=Ae^{x/L}+Be^{-x/L}$

PI: $n=Gt_n$

$$n = Ae^{x/L} + Be^{-x/L} + Gt_n$$

$$J_n = eD_n \frac{dn}{dx} = \frac{eD_n}{L}\left(Ae^{x/L} - Be^{-x/L}\right)$$

Applying BCs:

$$J_n(d) = 0 \quad \Rightarrow \quad B = Ae^{2d/L}$$

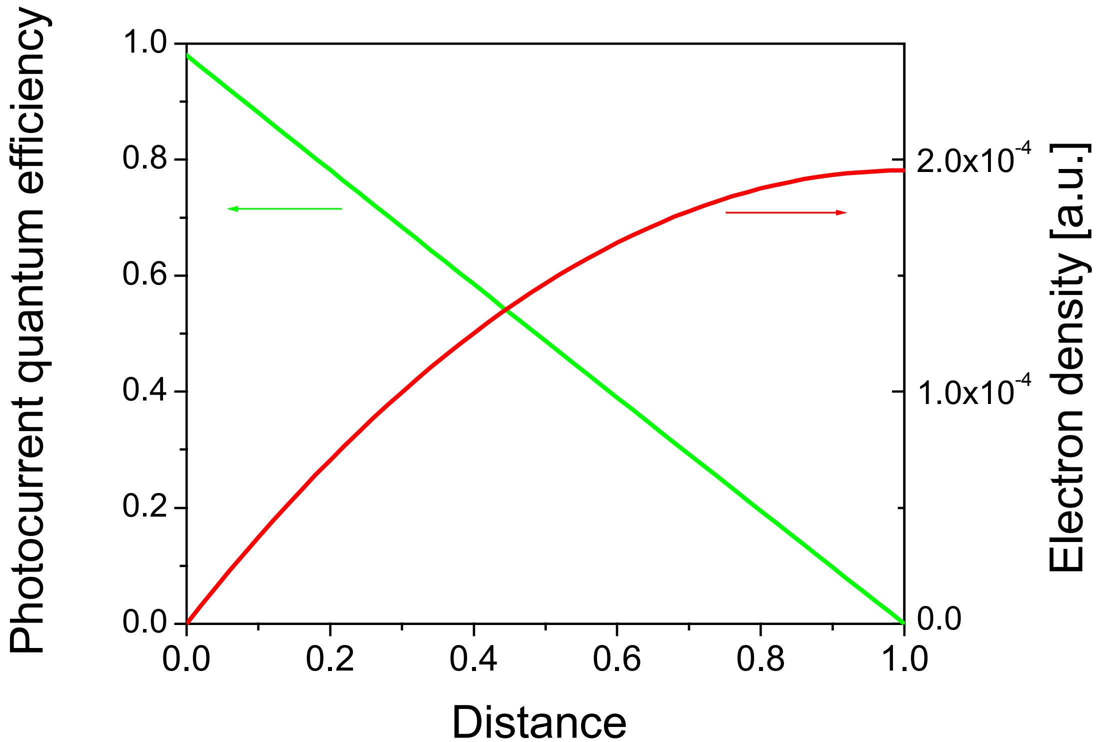
$$n(0) = 0 \quad \Rightarrow \quad A = \frac{-Gt_n}{\left(1 + e^{2d/L}\right)}$$

$$A = \frac{-Gt_n e^{-d/L}}{2\cosh(d/L)} \qquad B = \frac{-Gt_n e^{d/L}}{2\cosh(d/L)}$$

$$n = Gt_n - \frac{Gt_n e^{(x-d)/L}}{2\cosh(d/L)} - \frac{Gt_n e^{-(x-d)/L}}{2\cosh(d/L)} = Gt_n\left\{1 - \frac{\cosh((x-d)/L)}{\cosh(d/L)}\right\}$$

$$J_n = eD_n Gt_n \frac{1}{L}\frac{\sinh((d-x)/L)}{\cosh(d/L)} = eGL\frac{\sinh((d-x)/L)}{\cosh(d/L)}$$

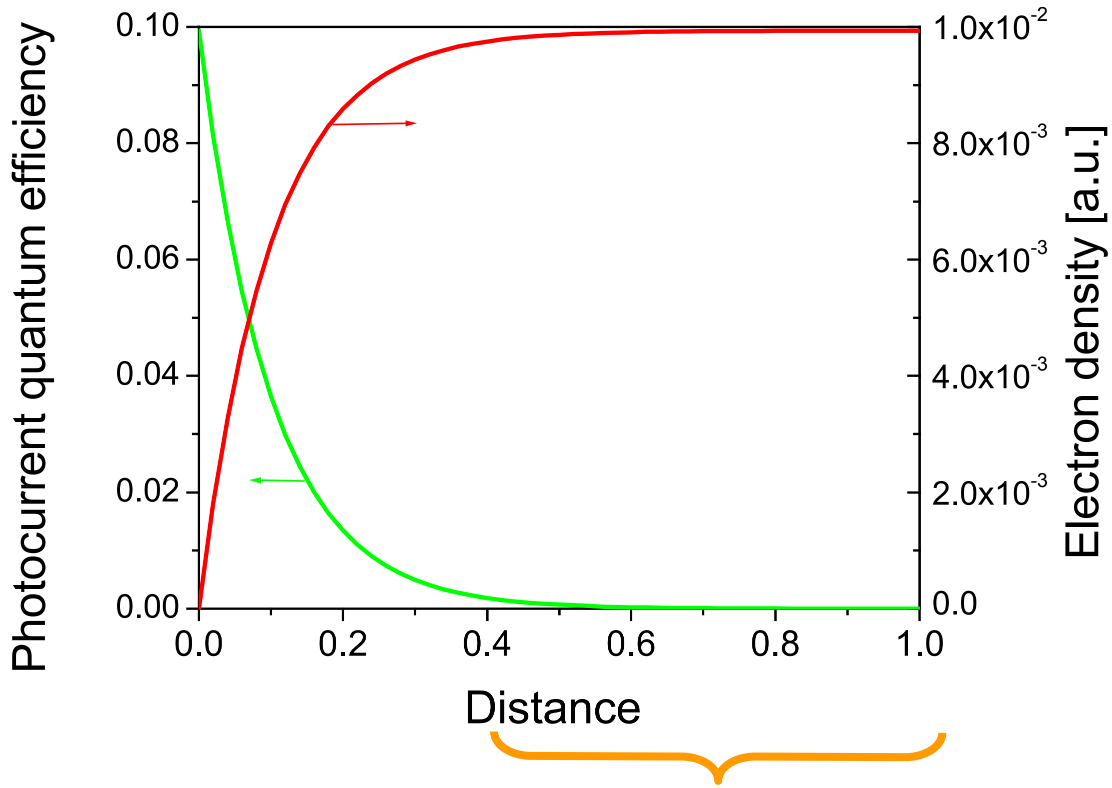
d = 1 μm, L = 5 μm, α = 5 μm^{-1}



High absorption, long diffusion length:

- all photons absorbed
- all electrons reach external circuit
- QE ~ 1

d = 1 μm, L = 0.1 μm, α = 5 μm^{-1}

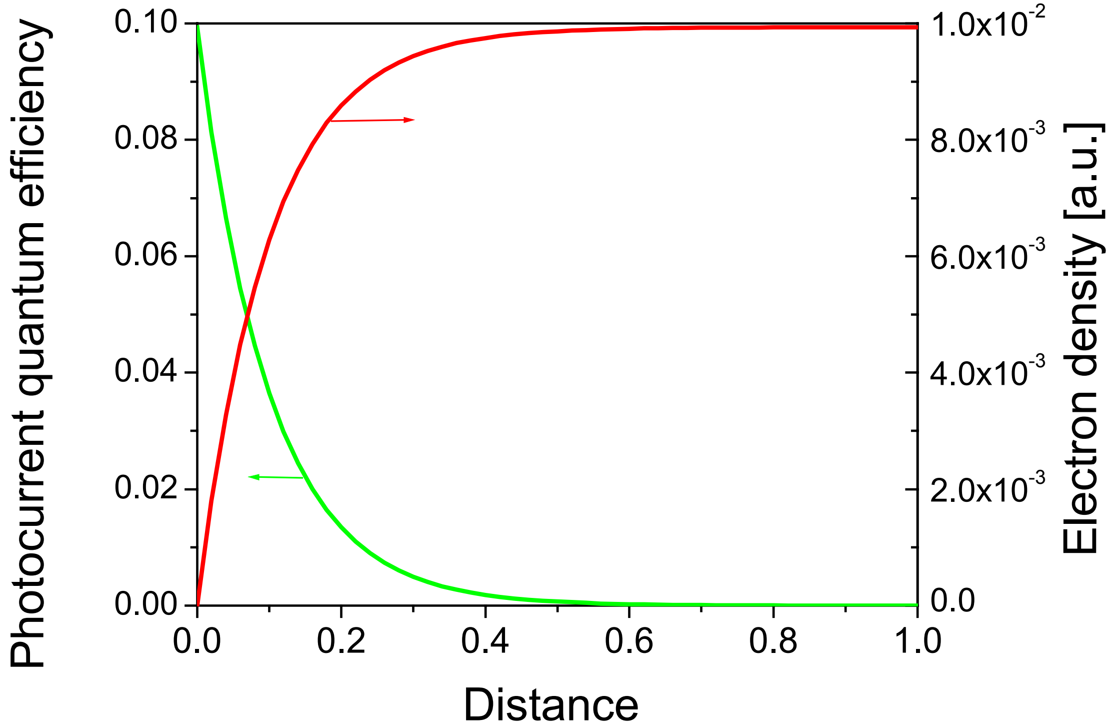


dJ/dx ~ 0

G = R

No useful photon absorption

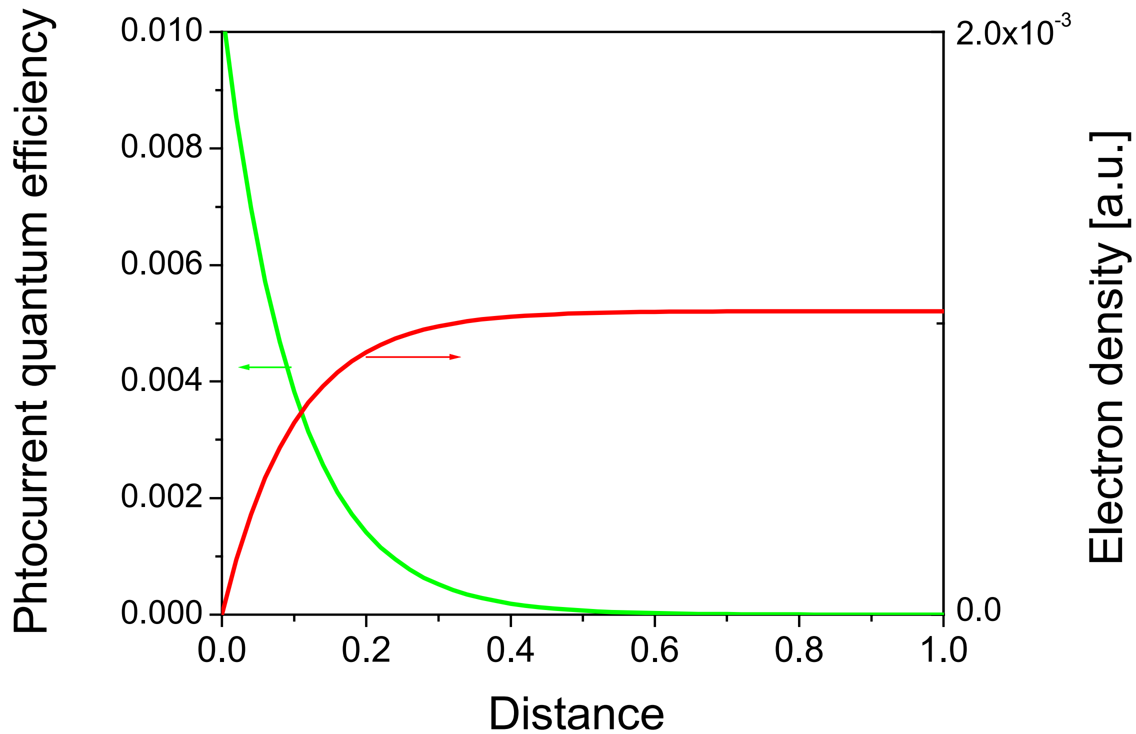
d = 1 μm, L = 0.1 μm, α = 5 μm^{-1}



High absorption, short diffusion length:

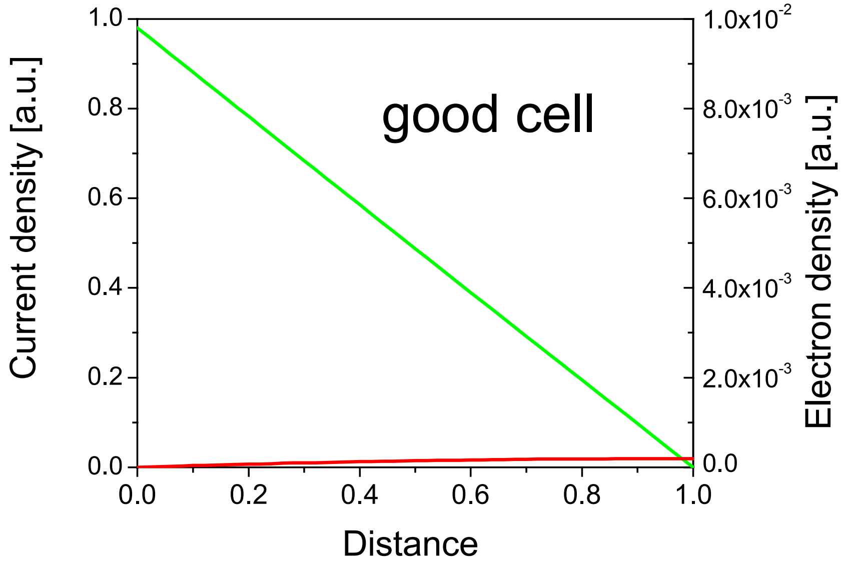
- all photons absorbed
- only ~ L/d of electrons reach external circuit
- QE ~ L/d

$d = 1\ \mu m$, $L = 0.1\ \mu m$, $\alpha = 0.1\ \mu m^{-1}$

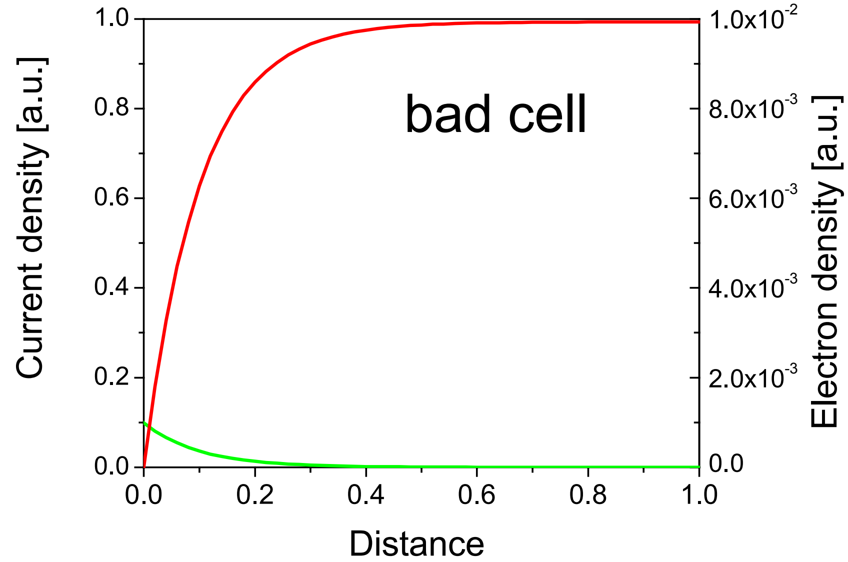


High absorption, short diffusion length:

- only $(1 - e^{-\alpha d})$ of photons absorbed
- only ~ L/d of electrons reach external circuit
- QE ~ $(1 - e^{-\alpha d}) * L/d$



good cell
Current density [a.u.]
Electron density [a.u.]
Distance
0.0
0.2
0.4
0.6
0.8
1.0
2.0x10^-3
4.0x10^-3
6.0x10^-3
8.0x10^-3
1.0x10^-2



bad cell
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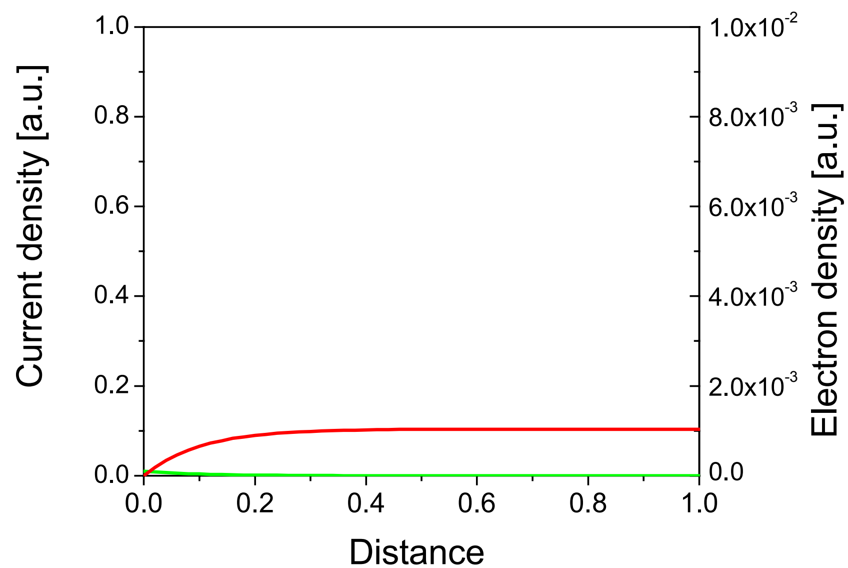

Current density [a.u.]
Electron density [a.u.]
Distance
0.0
0.2
0.4
0.6
0.8
1.0
2.0x10^-3
4.0x10^-3
6.0x10^-3
8.0x10^-3
1.0x10^-2

Summary of Lecture 21

- Continuity equation $$\frac{1}{e}\frac{dJ_n}{dx}+G-R=0$$
- *np* or *pn* junction provides asymmetric contacts $\Rightarrow$ directed photocurrent
- Simple model of a PV cell:
  - *n-p* junction with very thin *n* region, *p* region with thickness *d*,
  - spatially uniform generation rate *G*
  - electrons collected only through *n* contact (x = 0)
  - Photocurrent collected at x = 0: $$J_{SC}=J_n(0)=eGL\tanh(d/L)$$
- J_{SC} limited by
  - Generation rate. i.e. photon flux density, optical depth of slab
  - thickness of slab relative to electron diffusion length
- For large J_{SC} require L >> $1/\alpha$ i.e. very high purity material!