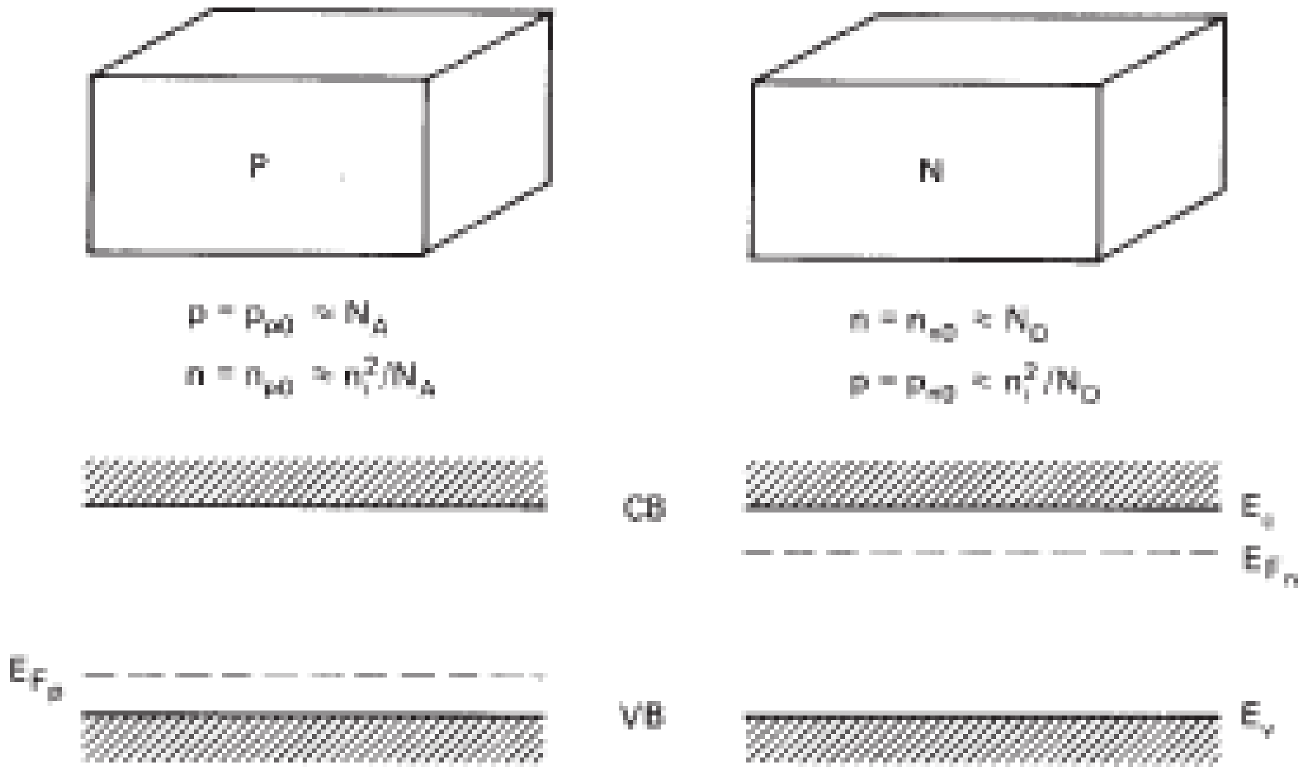
Solid state physics for Nano

UNIVERSITÄT SIEGEN
FESTKÖRPERPHYSIK

Lecture 7: pn junctons

Prof. Dr. U. Pietsch

pn-junction



Elements and principal band structure of pn- junction elements

Basis parameters

$$n_n p_n = n_p p_p = n_i^2$$

p_p – hole concentration at p-site - majority
p_n - hole concentration on n-site - minority

Due to charge carrier diffusion current, j_{Diff}, ionized (fixed) ions are left (A^- and D^+) originating an electric field, and subsequently drift current, j_{Drift} opposite to j_{Diff} of mobile charge carriers:
in equilibrium $j_{Diff} = - j_{Drift}$ → $j_{total} = 0$

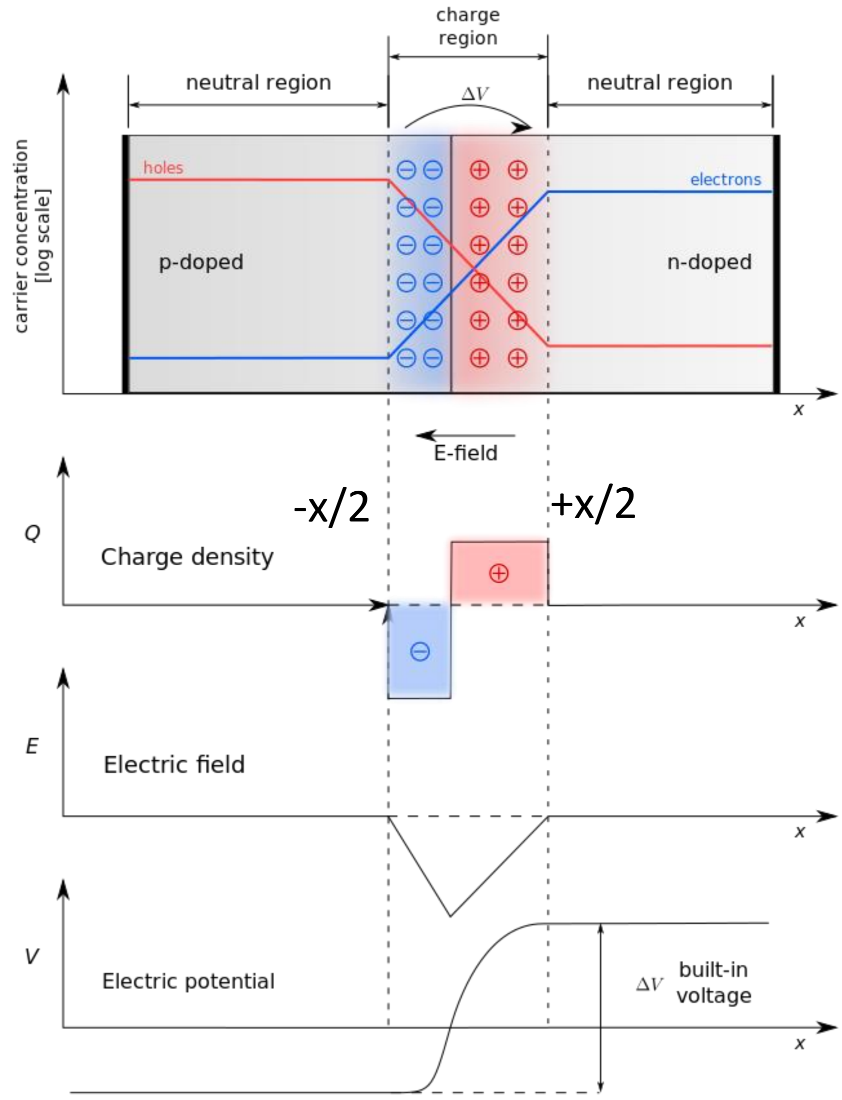
Originates contact potential: for hole current

$$\frac{dV_0}{dx}\frac{e}{kT} = -\frac{1}{p}\frac{dp}{dx}$$

V_p – potential on p site
V_n – potential on n-site

$$V_0 = \frac{kT}{e}\ln\frac{p_p}{p_n}$$

$p_p >> p_n$ → $V>0$



Because of $p_p = N_A$ and $p_n = n_i^2/N_D$,

$$V_0 = \frac{kT}{e}\ln\frac{p_p}{p_n} = \frac{kT}{e}\ln\frac{N_D N_A}{n_i^2} = \frac{kT}{e}\ln\frac{n_n}{n_p}$$

$$\frac{d^2V}{dx^2} = \begin{cases} -\frac{eN_A}{\varepsilon\varepsilon_r} \_ 0 < x_p < \frac{x}{2} \\ +\frac{eN_D}{\varepsilon\varepsilon_r} \_ -\frac{x}{2} < x_n < 0 \end{cases}$$

Boundary conditions: V=0; dV/dx=0 at $x_{n,p}=|x/2|$

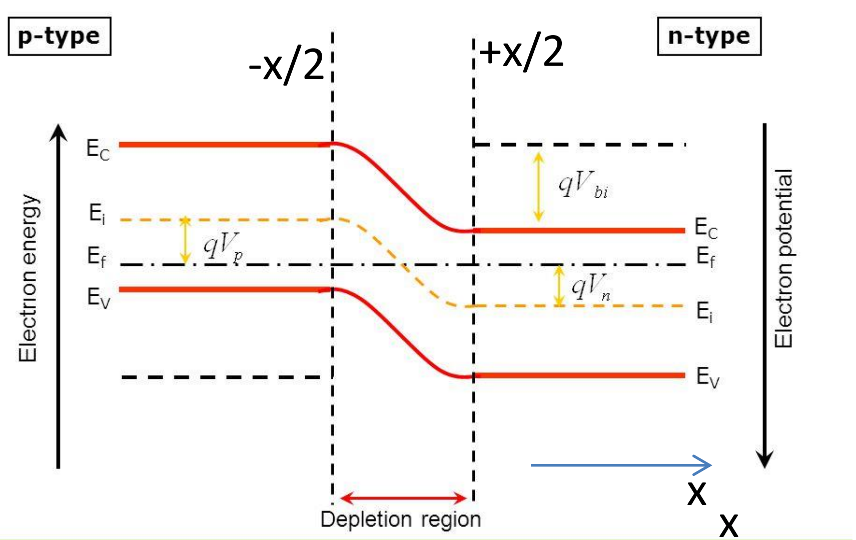
$$V_0(x) = -\frac{e}{2\varepsilon\varepsilon_r}(N_D x_n^2 + N_A x_p^2)$$

$$x_n = \sqrt{\frac{2V_0\varepsilon\varepsilon_r}{e}\frac{N_A}{N_D}\frac{1}{N_A+N_D}};\_\_\_ x_p = \frac{N_D}{N_A}x_n$$

$$E(x) = -gradV(x) = \frac{e}{\varepsilon\varepsilon_r}(N_D x_n + N_A x_p)$$

$$E_n(x) = -\frac{eN_D}{\varepsilon\varepsilon_r}x_n;....$$

p – n junction barrier height



$$x = \propto \sqrt{\frac{1}{N}}$$

Diffusion and drift current

$J=j_n+j_p$; electrons diffuse n→ p; and holes from p→n; stationary case d/dt=0

$$\frac{dj_p}{dx}=-\frac{dj_n}{dx}=-eU$$

$$j_n=eD_n\frac{dn}{dx}-e\mu_n n\frac{dV}{dx}$$

$$j_p=-eD_p\frac{dp}{dx}+e\mu_p p\frac{dV}{dx}$$

Diffusion Drift

For minority charge carriers neglect drift current

$$j_n^{(p)}=eD_n\frac{dn}{dx};\_\_\ j_p^{(n)}=-eD_p\frac{dp}{dx}$$

For majority charge carriers neglect diffusion current

$$j_n^{(n)}=-e\mu_n n\frac{dV}{dx};\_\_\ j_p^{(p)}=e\mu_p p\frac{dV}{dx}$$

Outside space charge diffusion current depends on drift current of minority charge carriers because here → dV/dx=0

$$\frac{d^2 p}{dx^2} = -\frac{1}{eD_p}\frac{dj_p^{(n)}}{dx} = \frac{V}{D_p} = \frac{p-p_n}{L_p^2}; \_\_\_\_\_\_ \frac{d^2 n}{dx^2} = \frac{n-n_p}{L_n^2}$$

Generell solution

$$p = p_n + A_1 \exp(x/L_p) + A_2 \exp(-x/L_p)$$

$$n = n_p + B_1 \exp(x/L_n) + B_2 \exp(-x/L_n)$$

p → p_n for x →+∞ and n→n_p for x→ -∞ ; therefore A_1 = B_2 =0

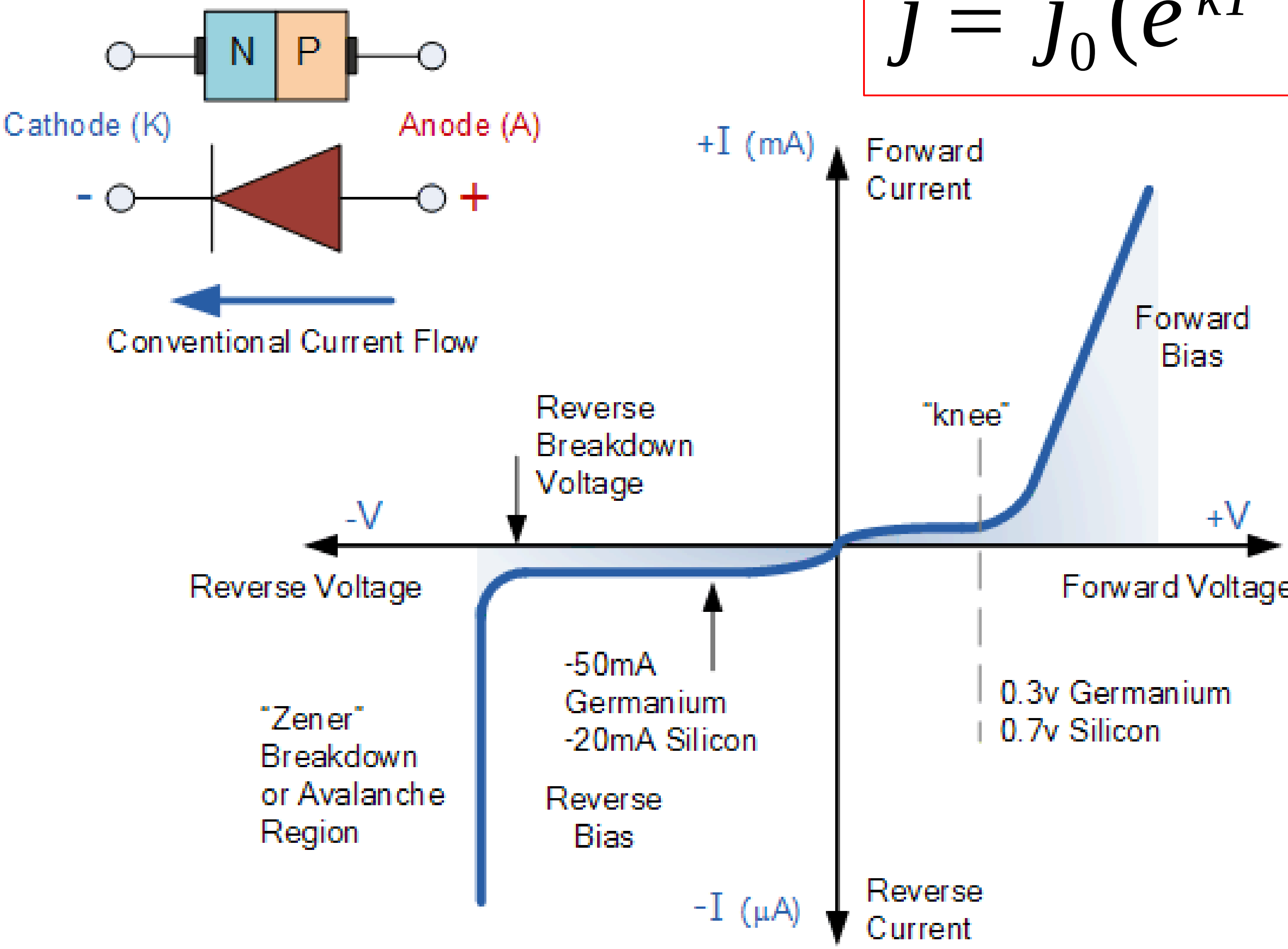
From Poisson equation: $A_2 = p_n(e^{\frac{eU}{kT}} - 1)e^{x/L_p}; \_\_\_\_\_\_ B_1 = n_p(e^{\frac{eU}{kT}} - 1)e^{-x/L_n}$

$$p(x) = p_n + p_n[e^{eU/kT} - 1]e^{(x_n - x)/L_p}; \_\_\_\_ n(x) = n_p + n_p[e^{eU/kT} - 1]e^{(x - x_p)/L_n}$$

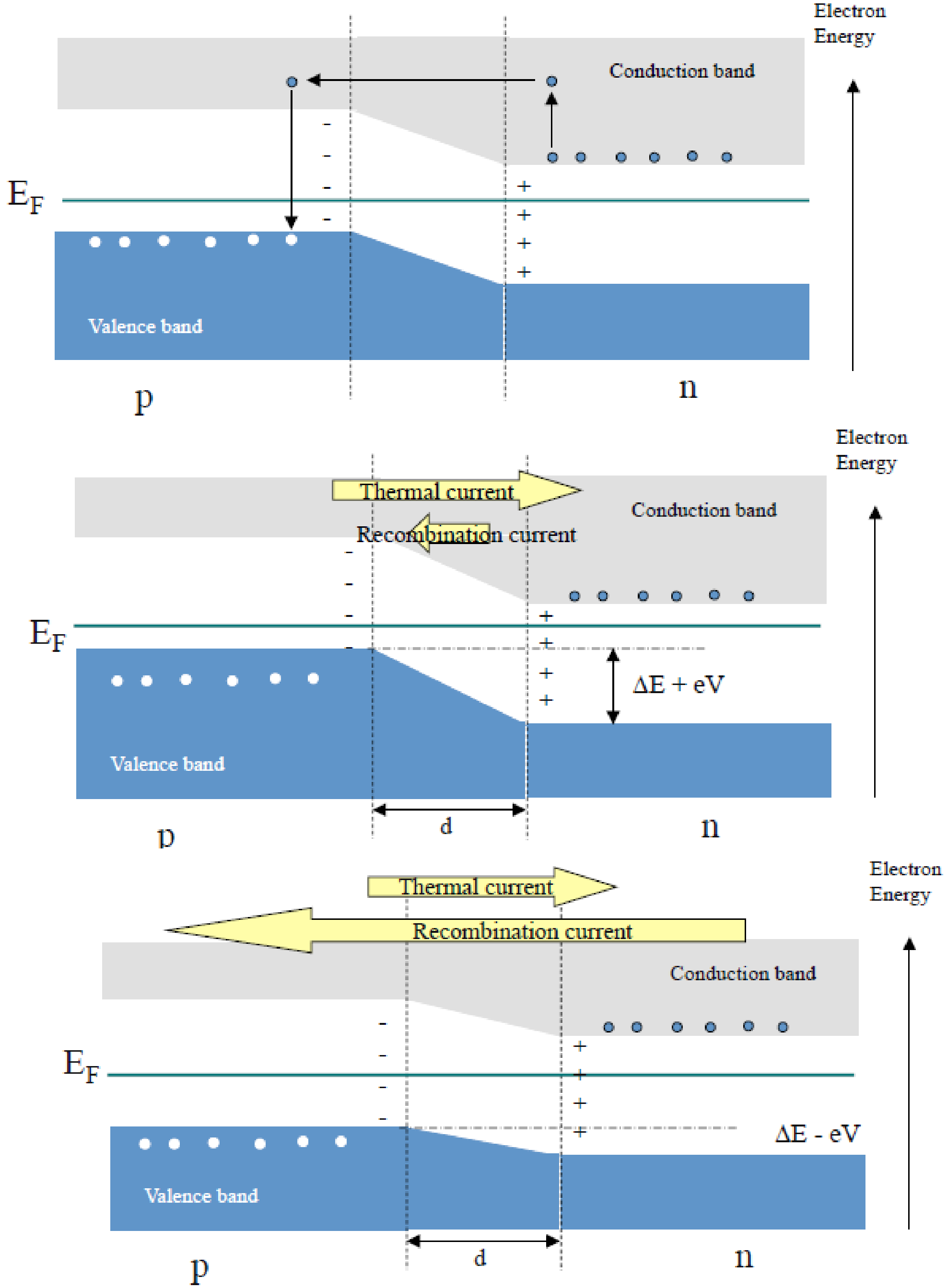
$$j_p^{(n)}(x) = e\frac{D_p}{L_p} p_n[e^{eU/kT} - 1]e^{(x_n - x)/L_p}; \_\_\_\_ j_n^{(p)}(x) = \frac{eD_n}{L_n} n_p[e^{eU/kT} - 1]e^{(x - x_p)/L_n}$$

$$j = j_p^{(n)}(x) + j_n^{(p)}(x) = e(\frac{D_p}{L_p} p_n + \frac{eD_n}{L_n} n_p)(e^{\frac{eU}{kT}} - 1)$$

$$j = j_0\left(e^{\frac{eU}{kT}} - 1\right)$$



Potential offset



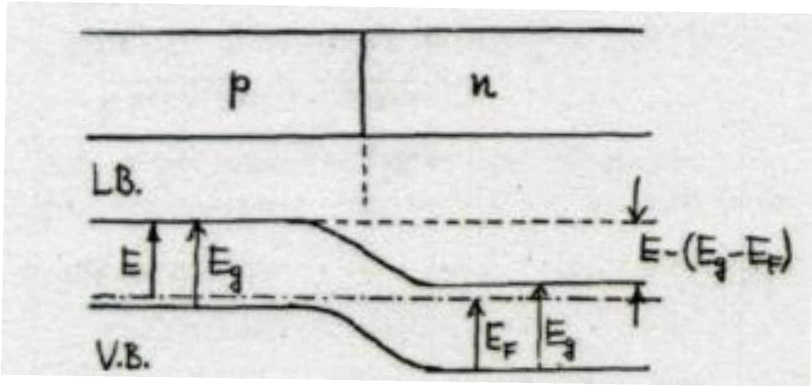
Equilibrium

Reverse bias

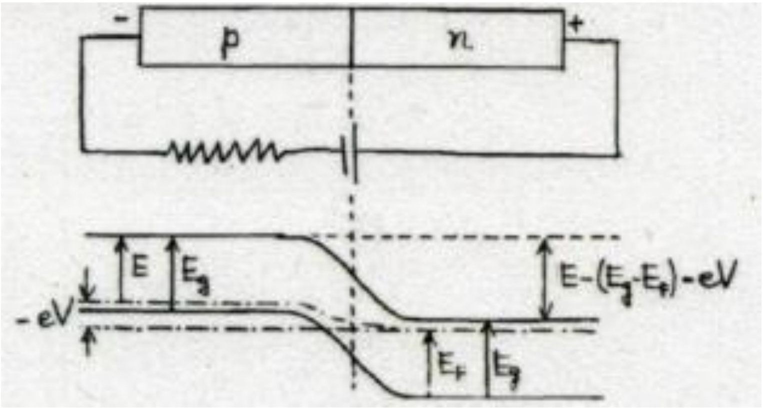
Foreward bias

http://faculty.cord.edu/luther/physics225/Handouts/semiconductors_handout.pdf

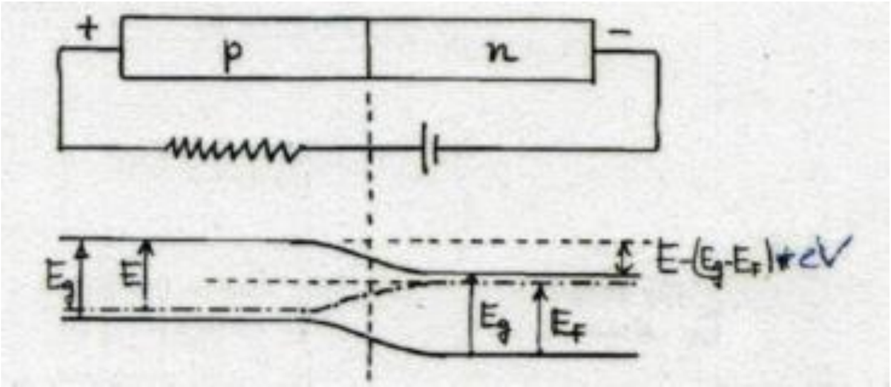
Potential offset



Equilibrium



Reverse bias



Foreward bias

J. Peisl, LMU 1990

pn-junction under illumination

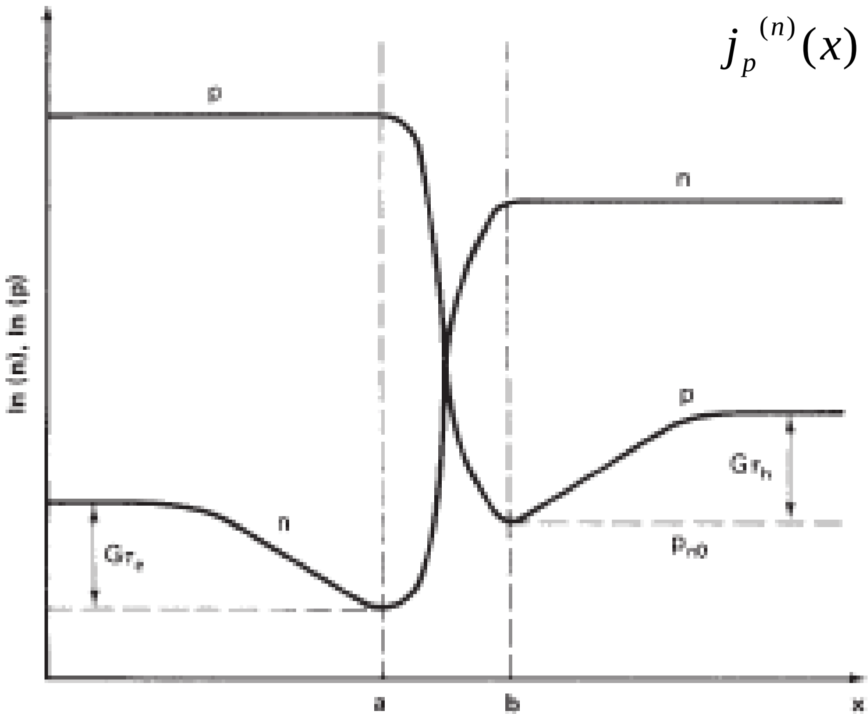
Generation of carriers by light:
(see also page 6)

$$\frac{d^2p}{dx^2}=\frac{p-p_n}{L_p^2}-\frac{G}{D_p};\qquad \frac{d^2n}{dx^2}=\frac{n-n_p}{L_n^2}-\frac{G}{D_n}$$

G – generation rate

$$p(x)=p_n+G\tau_e+[p_n(e^{eU/kT}-1)-G\tau_h]e^{(x_n-x)/L_p}$$

$$j_p^{(n)}(x)=e\frac{D_p}{L_p}p_n[e^{eU/kT}-1]e^{(x_n-x)/L_p}-eGL_ne^{(x_n-x)/L_p}$$



$\rightarrow$

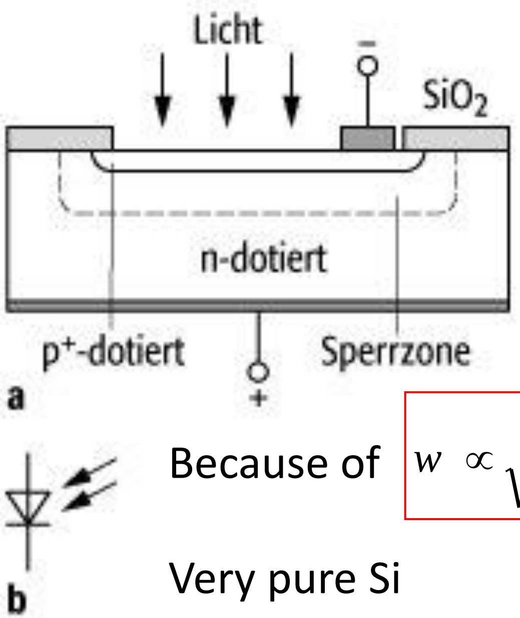
$$j=j_0(e^{eU/kT}-1)-j_L$$

$$I=I_s\left[\exp\left(\frac{eU}{kT}\right)-1\right]-I_L$$

$$I_L=eAG(L_n+L_p+W)$$

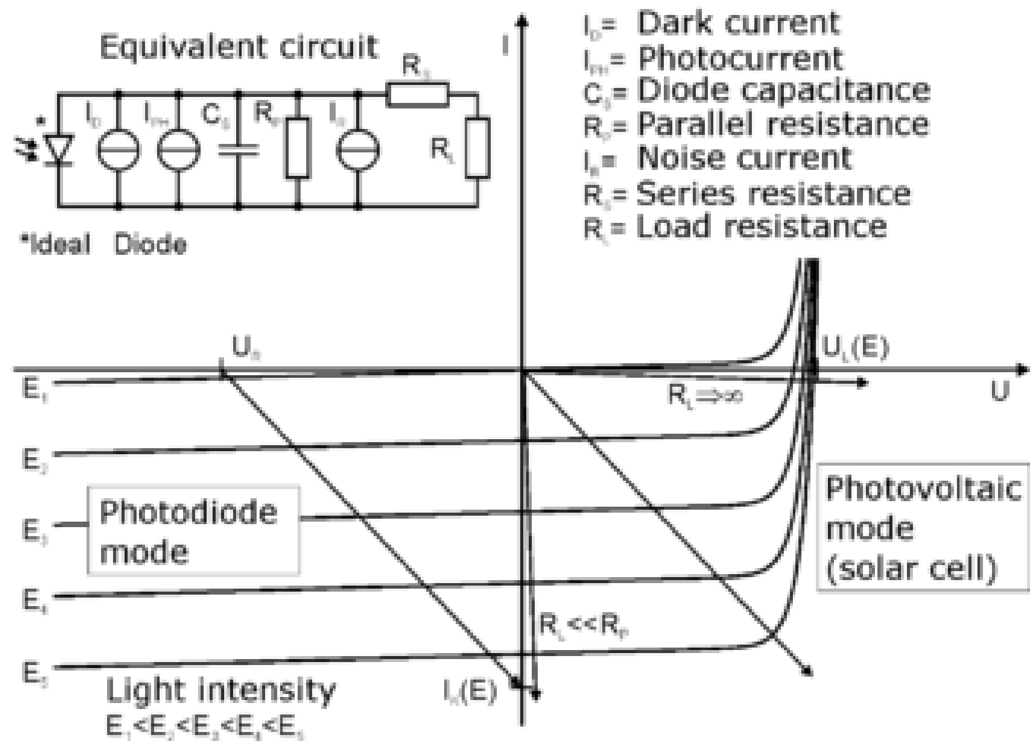
I_L - Leakage current

Photo -diode



Because of $w \propto \sqrt{\dfrac{U}{N}}$

Very pure Si material



Creation of e-h – pairs within the space charge region, because of reverse bias, e and h become separated towards external contacts. Number of created e-h pairs depends on photon energy: $E_g(k=0)$ – Si – 3.56eV

$$N = h\nu / E_g(k=0)$$

hν=10keV, N = 2808

Pn-CCD

Diffusion length

External irradiation creates a charge carrier excess at the SC surface. This excess decays exponentially towards the bulk : diffusion length

Recombination excess : $U_n = \frac{\Delta n}{\tau_n}$ ___ $U_p = \frac{\Delta p}{\tau_p}$

$$\frac{d\Delta p}{dt} = G - \frac{\Delta p}{\tau_p} - \frac{1}{e} divj_p$$

$$\frac{d\Delta n}{dt} = G - \frac{\Delta n}{\tau_n} - \frac{1}{e} divj_n$$

G=0 in bulk, without E-field $j_n = eD_n grad\Delta n$ ___ $j_p = eD_p grad\Delta p$

Solve Poisson equation : divgrad(z)=d²/dz²

$$-\frac{\Delta p}{\tau_p} + D_p \frac{d^2\Delta p}{dz^2} = 0$$

$$-\frac{\Delta n}{\tau_n} + D_n \frac{d^2\Delta n}{dz^2} = 0$$

Ansatz: $\Delta\rho = \rho_0 e^{\frac{-z}{L_p}}$ ___ $\Delta n = n_0 e^{\frac{-z}{L_n}}$

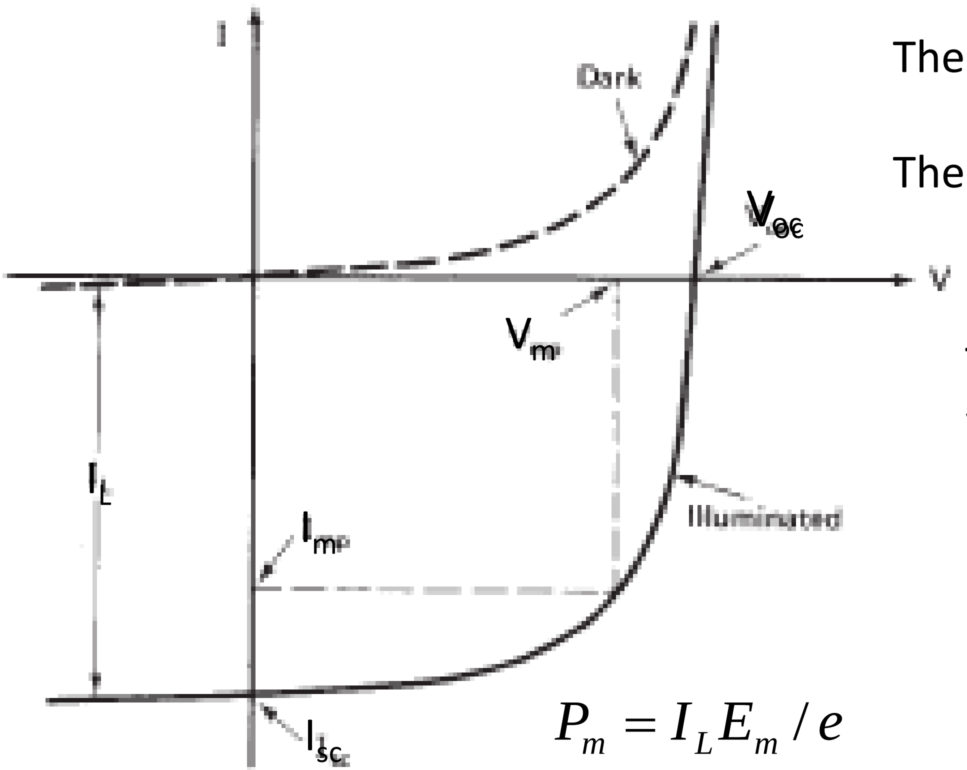
Diffusion length

$$L_p = \sqrt{\tau_p D_p} \quad \_\_\_ \quad L_n = \sqrt{\tau_n D_n}$$

Solar cells

Solar cell operates between $-1 < I < 0A$ and $0 < V < 1V$.
open-circuit voltage V_{oc} is for $I=0$. At $V=0$ the $I=I_L$ is the short-circuit current.
Only the rectangle I_{sc} x V_{oc} can be used for power conversion; load resistance R_L sets the working point at I_m and V_m defining the filling factor .

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} < 1$$



$$P_m = I_L E_m / e$$

power conversion efficiency $$\eta = \frac{P_m}{P_{in}}$$

The open circuit voltage: $$V_{oc} = \frac{KT}{e} \ln\left(\frac{I_L}{I_s} + 1\right)$$

The output power is

$$P = IV = I_s V \left[\exp\left(\frac{eV}{kT}\right) - 1 \right] - I_L V$$

The condition dP/dV=0 defines the working point for V_m

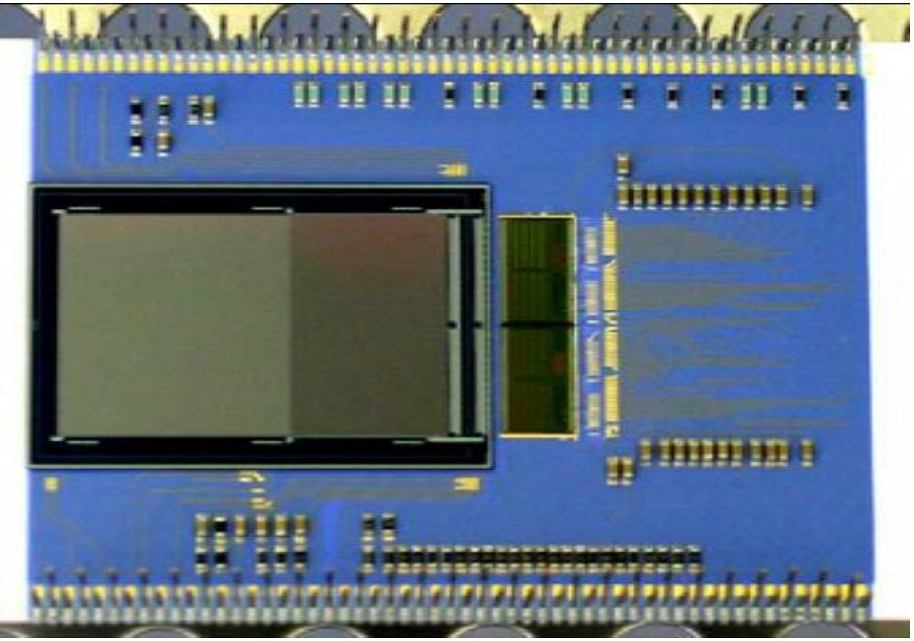
$$V_m = V_{oc} - \frac{kT}{e} \ln\left(1 + \frac{kT}{eV_m}\right)$$

and approximate for I_m $$I_m \approx I_L \left(1 - \frac{kT}{eV_m}\right)$$

Energy delivered per photon at R_L

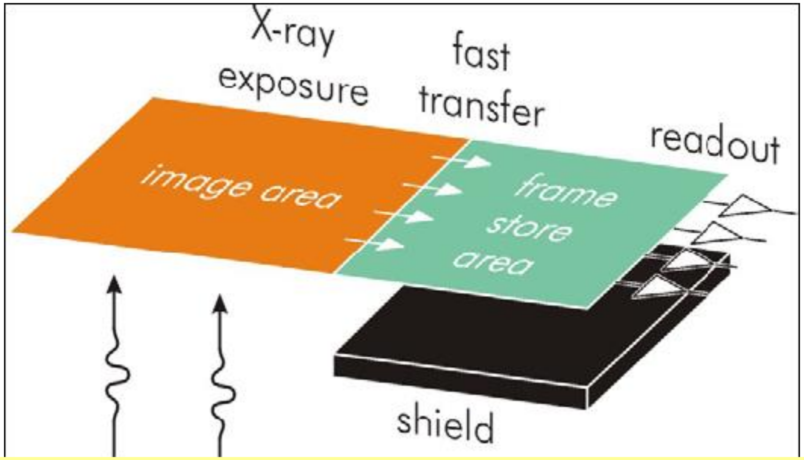
$$E_m = e\left[V_{oc} - \frac{kT}{e} \ln\left(1 + \frac{kT}{eV_m}\right) - \frac{kT}{e} \right]$$

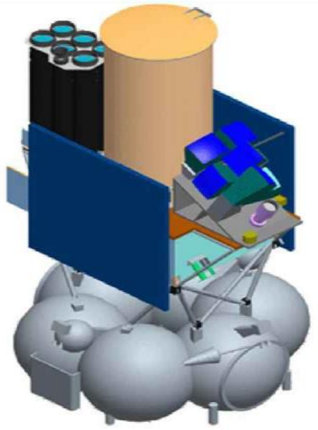
Energy dispersive pixel detector for X-rays



Alternative approach

Project has started June2007

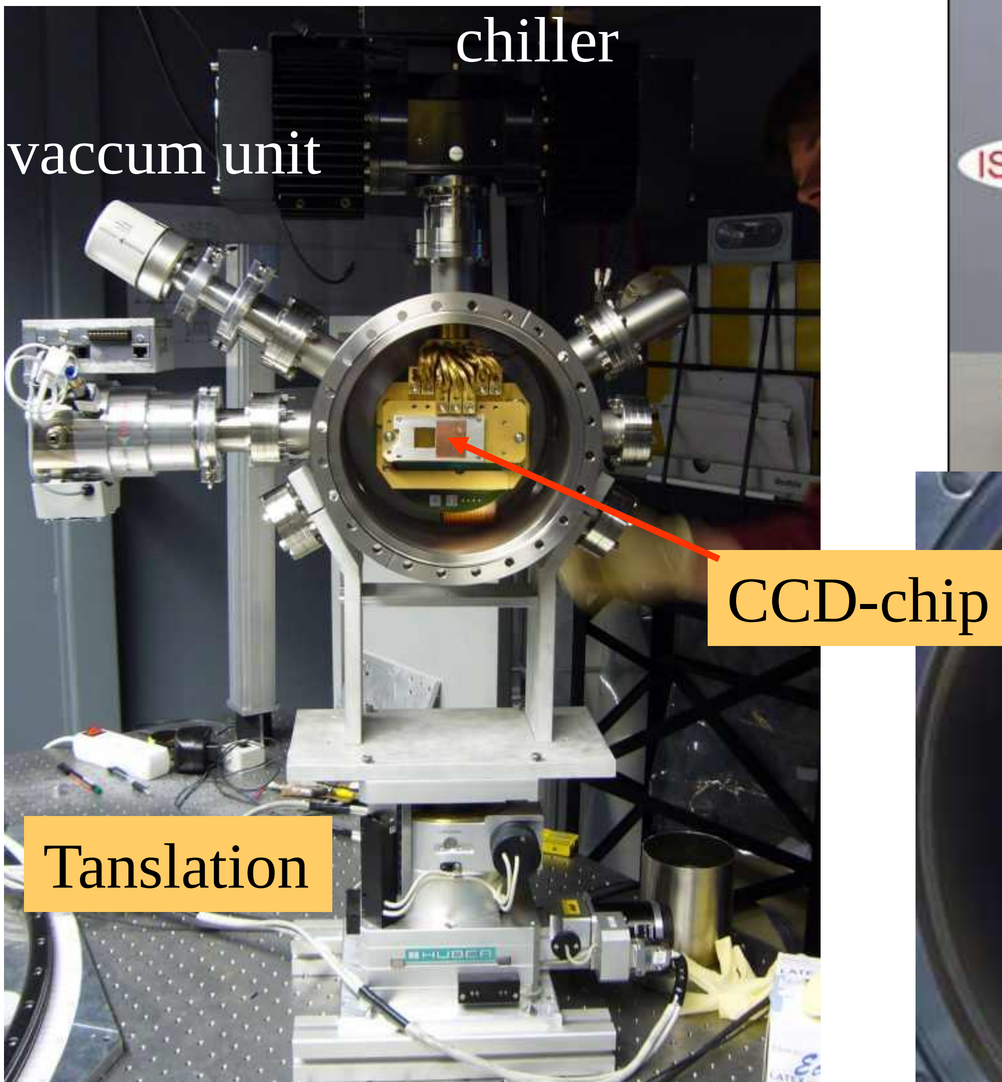


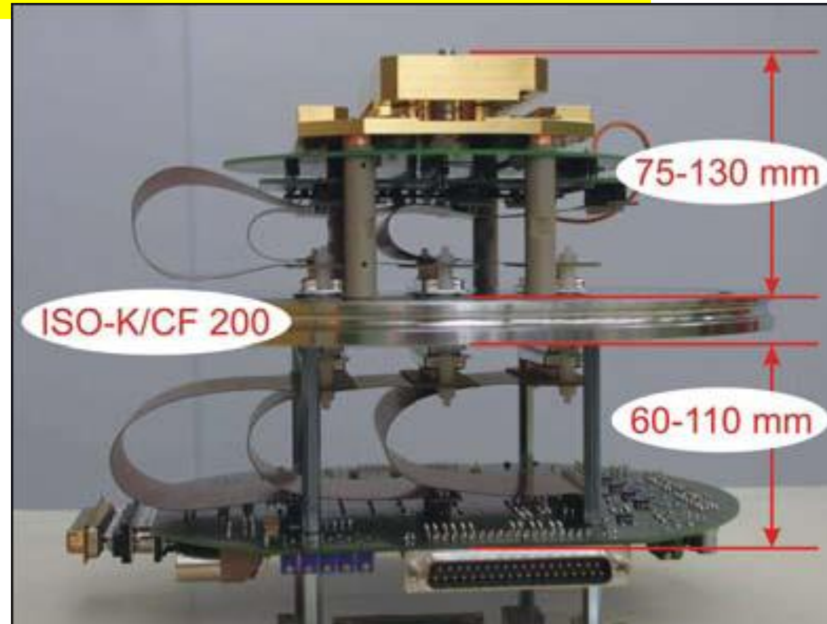


pn-CCD X-ray detector type of MPI HLL Munich, originally *developed for* XMM-Newton Satellite mission (ESA).
Since launch 1999 excellent spectroscopy and imaging,

Our Project : Application of pnCCD for use of Synchrotron Radiation

General setup of the detector





Application: Laue diffraction at Lithium aluminate ($LiAlO_2$ [100])

→ tetragonal structure

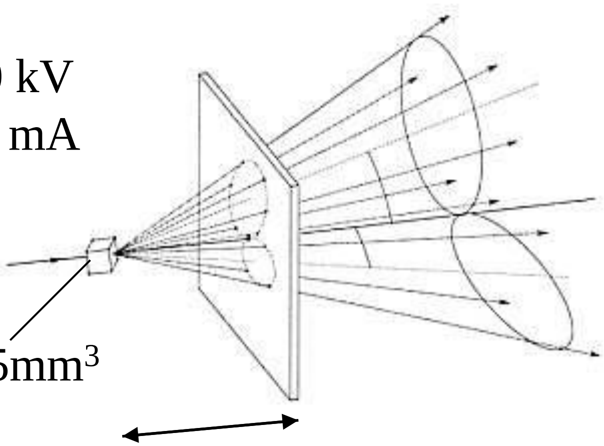
$$a = 5.1687 \text{ Å}$$
$$c = 6.2676 \text{ Å}$$

Illumination parallel 100

U = 40 kV
I = 30 mA

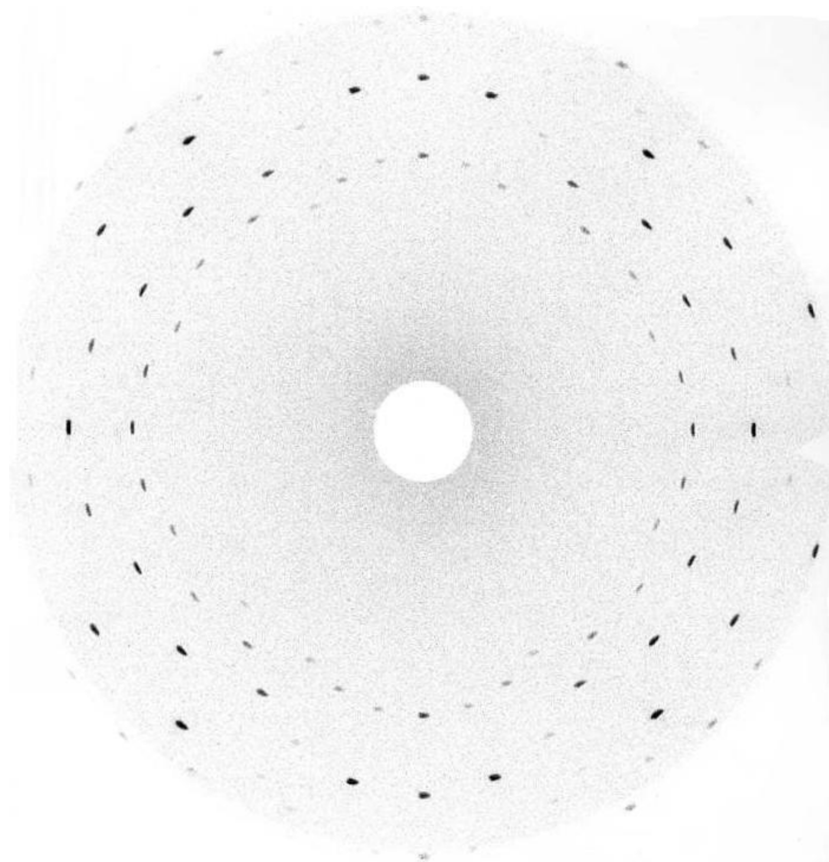
X-ray

10x10x0.5mm^3



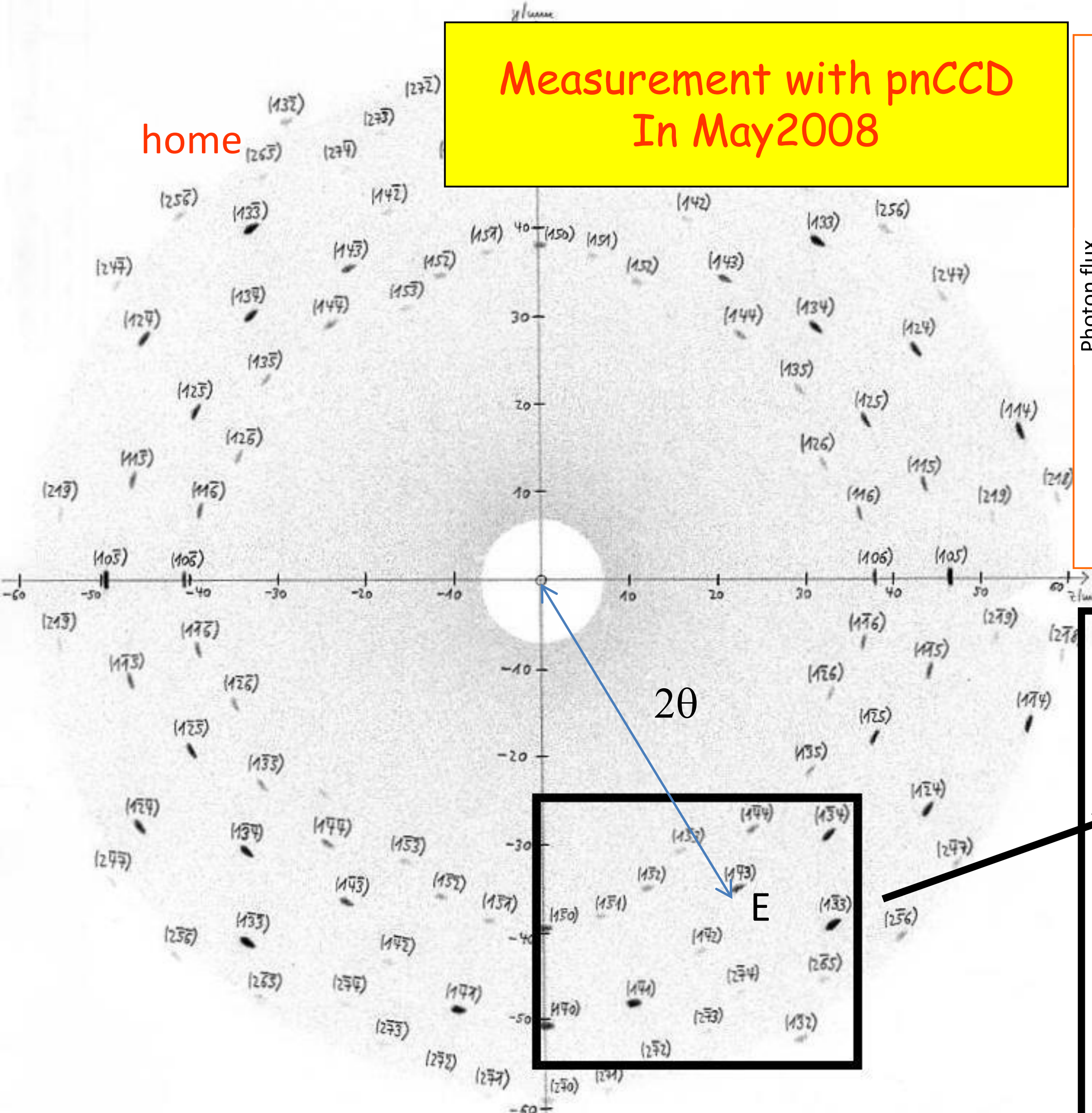
d_x ~ 95mm

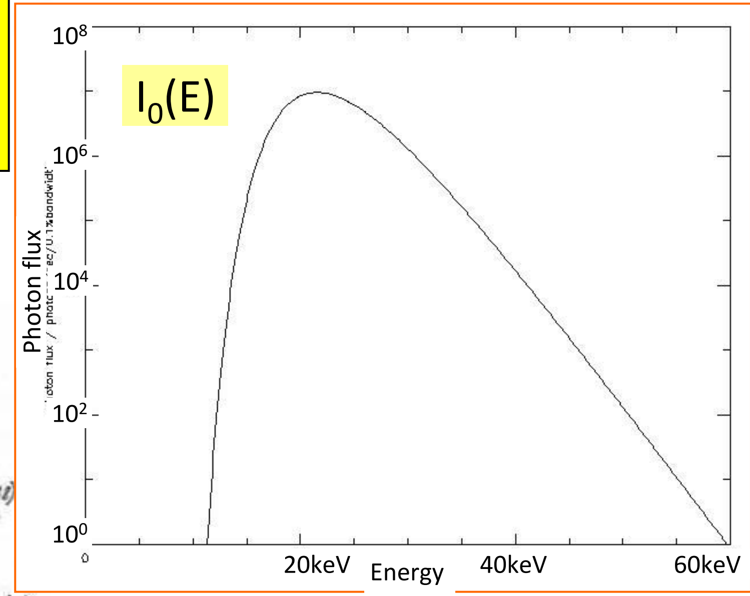
t ~ 15min

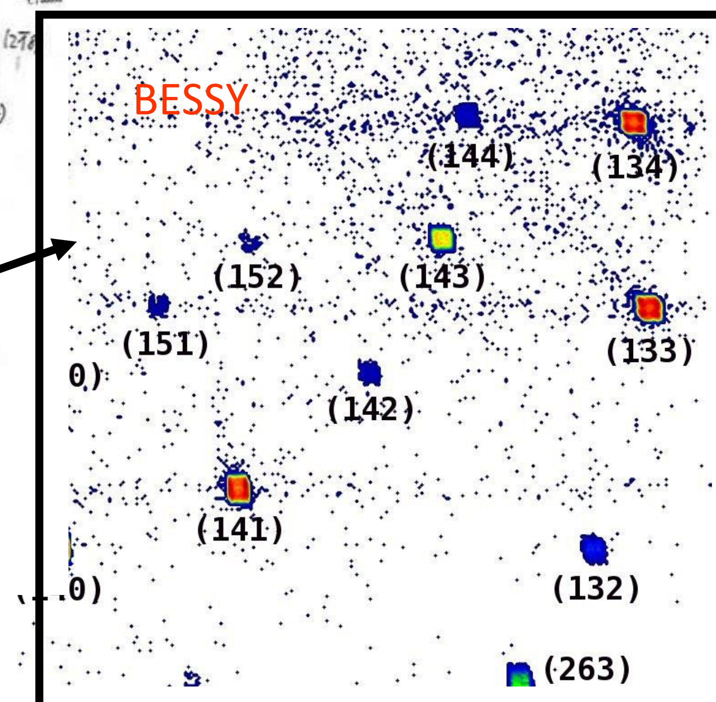


2-fold symmetry!

Measurement with pnCCD
In May2008



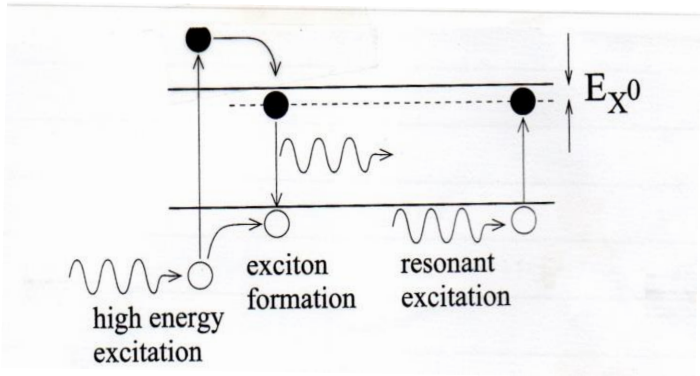


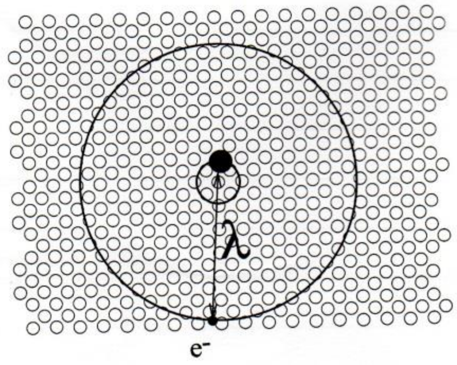


Measure Bragg angle and energy simulataneous

$E = hc/(d \sin\theta)$

Excitons in semiconductors





Excitons are created once a photon is absorbed by the semiconductor exciting an electron from VB into CB creating h+ in VB and e- in CB connected via Coulomb interaction.

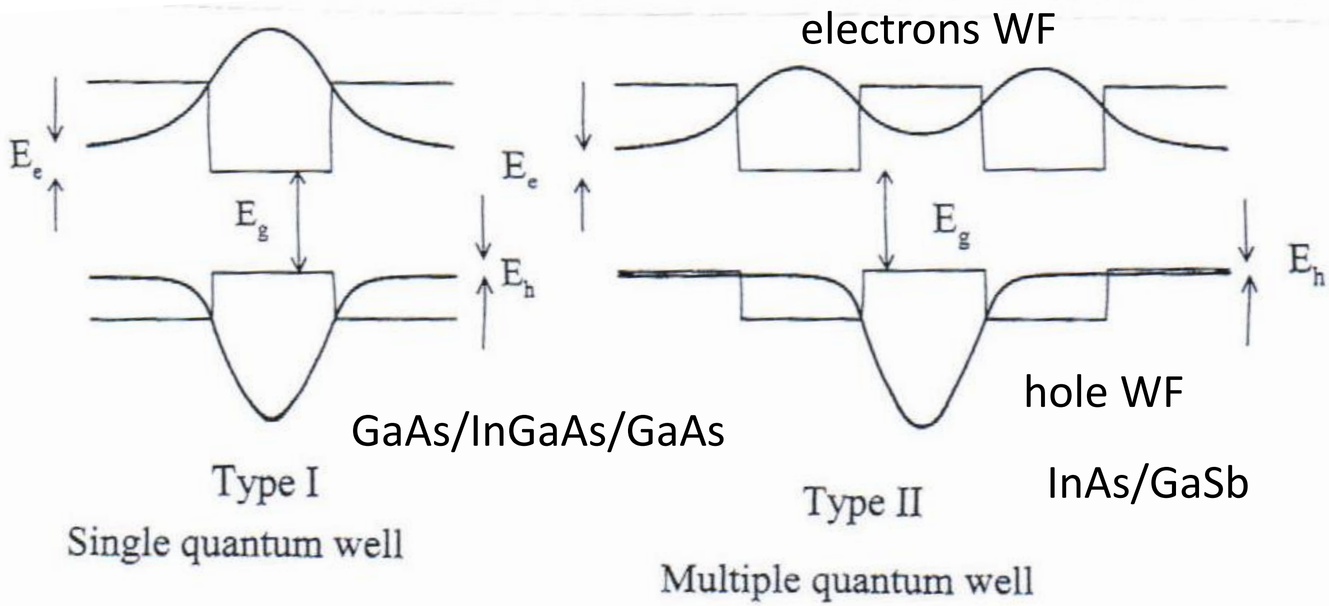
→ bound electron-hole pair = “exciton”, is quite stable and can have a long life time, of order of nanoseconds.

Exciton binding energy $E_X = 13.6eV \frac{\mu}{\varepsilon_r{}^2} \frac{1}{n^2}$ exciton radius $\lambda_x = 0.0529nm \frac{\varepsilon_r}{\mu} n^2$

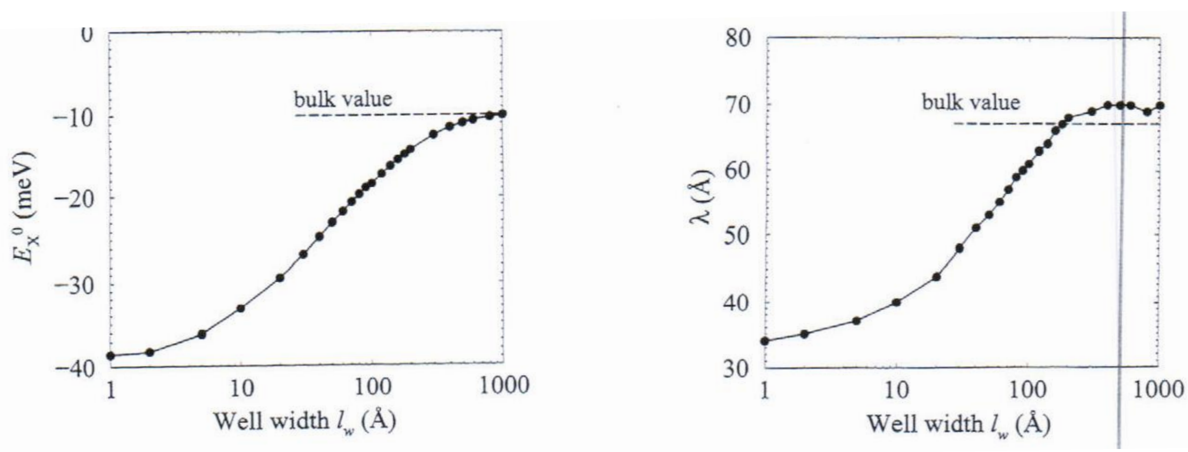
Considering reduced mass $\frac{1}{\mu} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$

In case of GaAs m^*_e=0.067m and m_{hh}*= 0.62m → μ=0.060m. Using e_r =13.18 the exciton binding energy is E_x=-4.7 meV and the Bohr radius λ=11.5nm.

Excitons in heterostructures



Thin well structures



$$\lim_{l_w \to \infty} E_{X^0} = E_{X^0}^{3D} \quad \text{and} \quad \lim_{l_w \to 0} E_{X^0} = 4E_{X^0}^{3D}$$

pn semiconductor diode (LED)

Super luminescent LED (SLD)

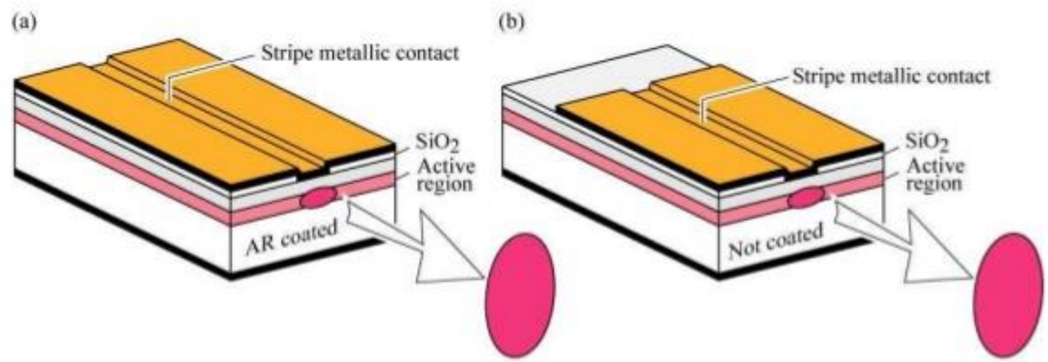
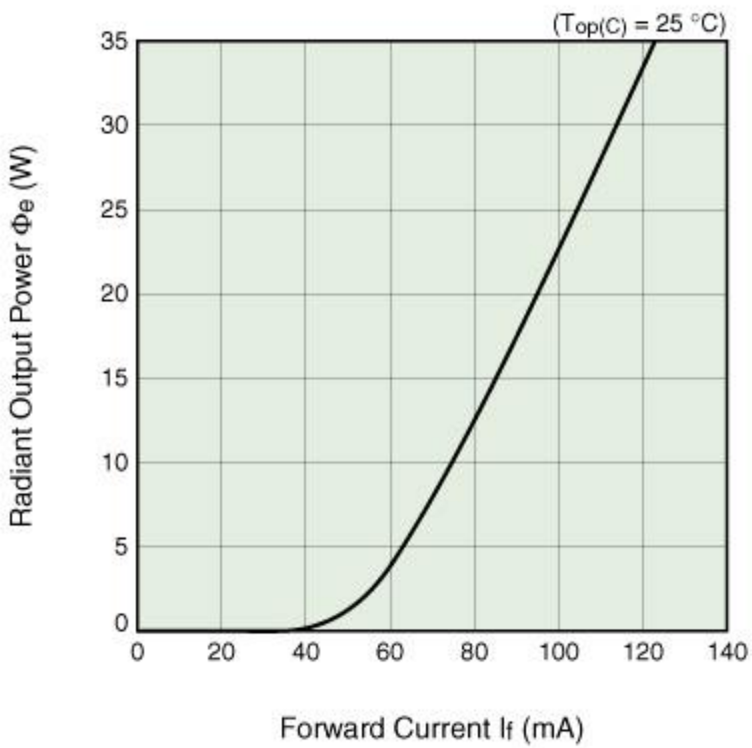
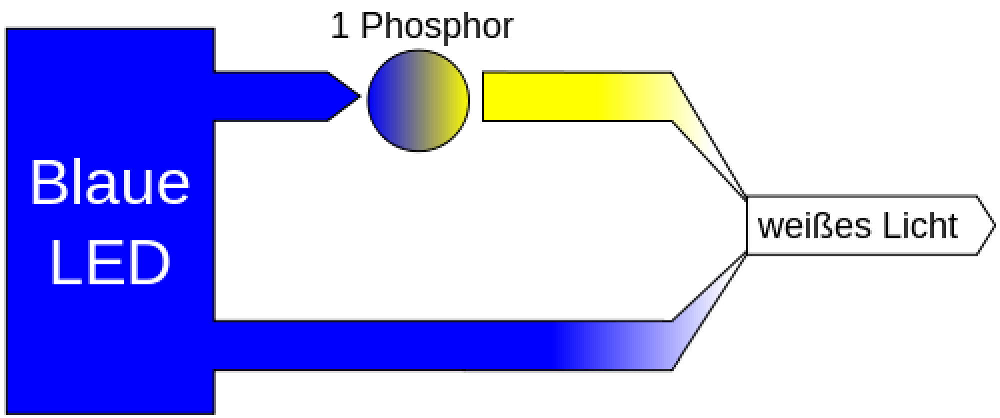


Fig. 23.9. Common structures of superluminescent diodes (SLDs). (a) SLD with cleaved facets coated with anti-reflection (AR) coatings. (b) SLD with cleaved, reflecting facets and stripe contact injecting current over the partial length of the device.



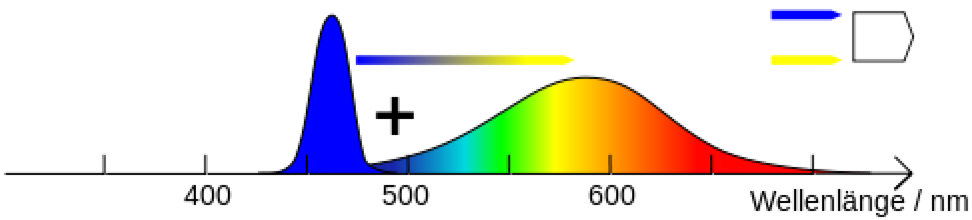
Radiant flux 30mW at operating voltage 1.8V

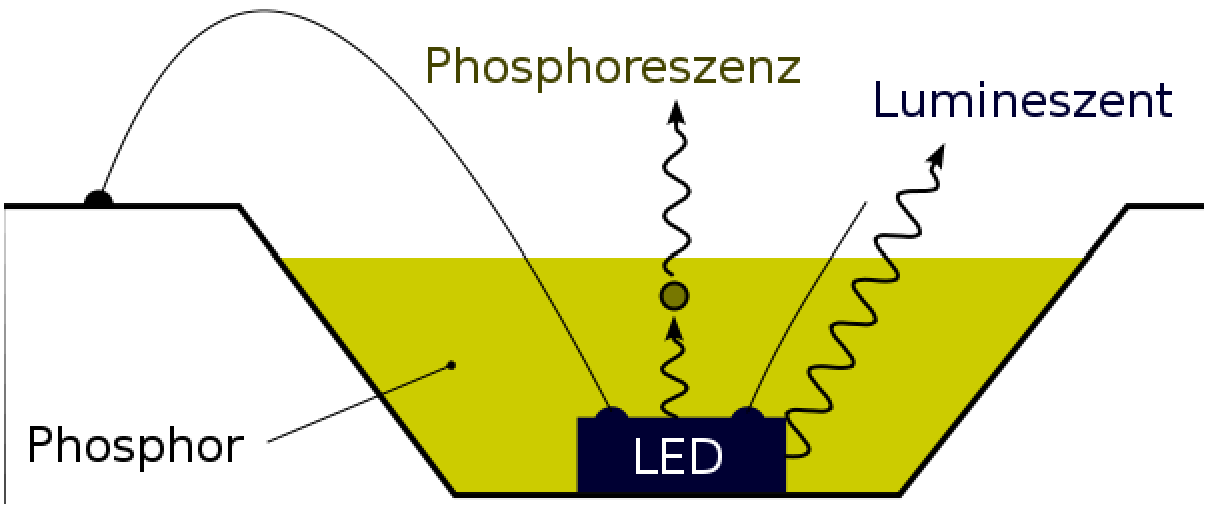
Hamamatsu GmbH



AlGaN - λ= 400nm

Withe LED

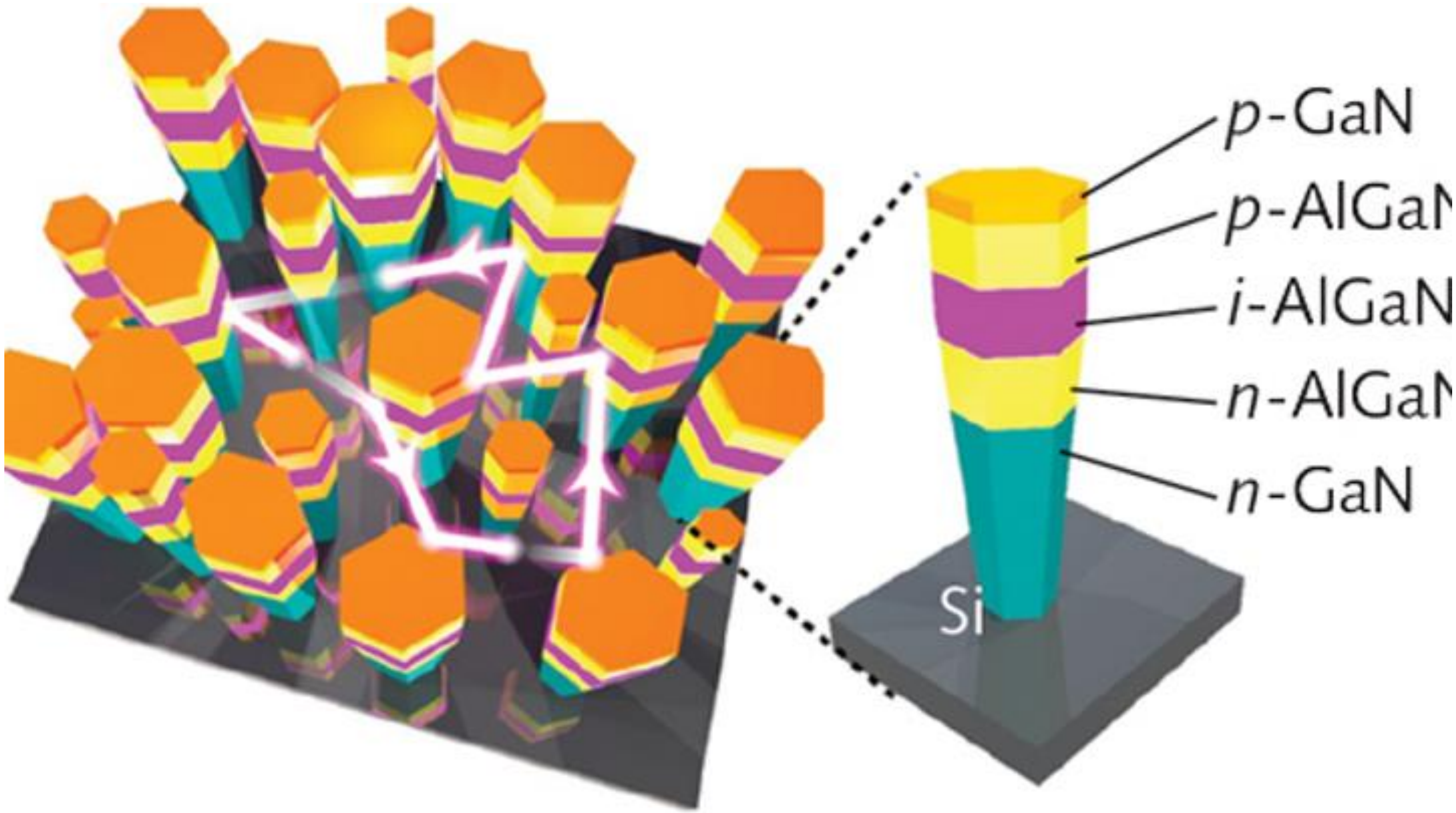




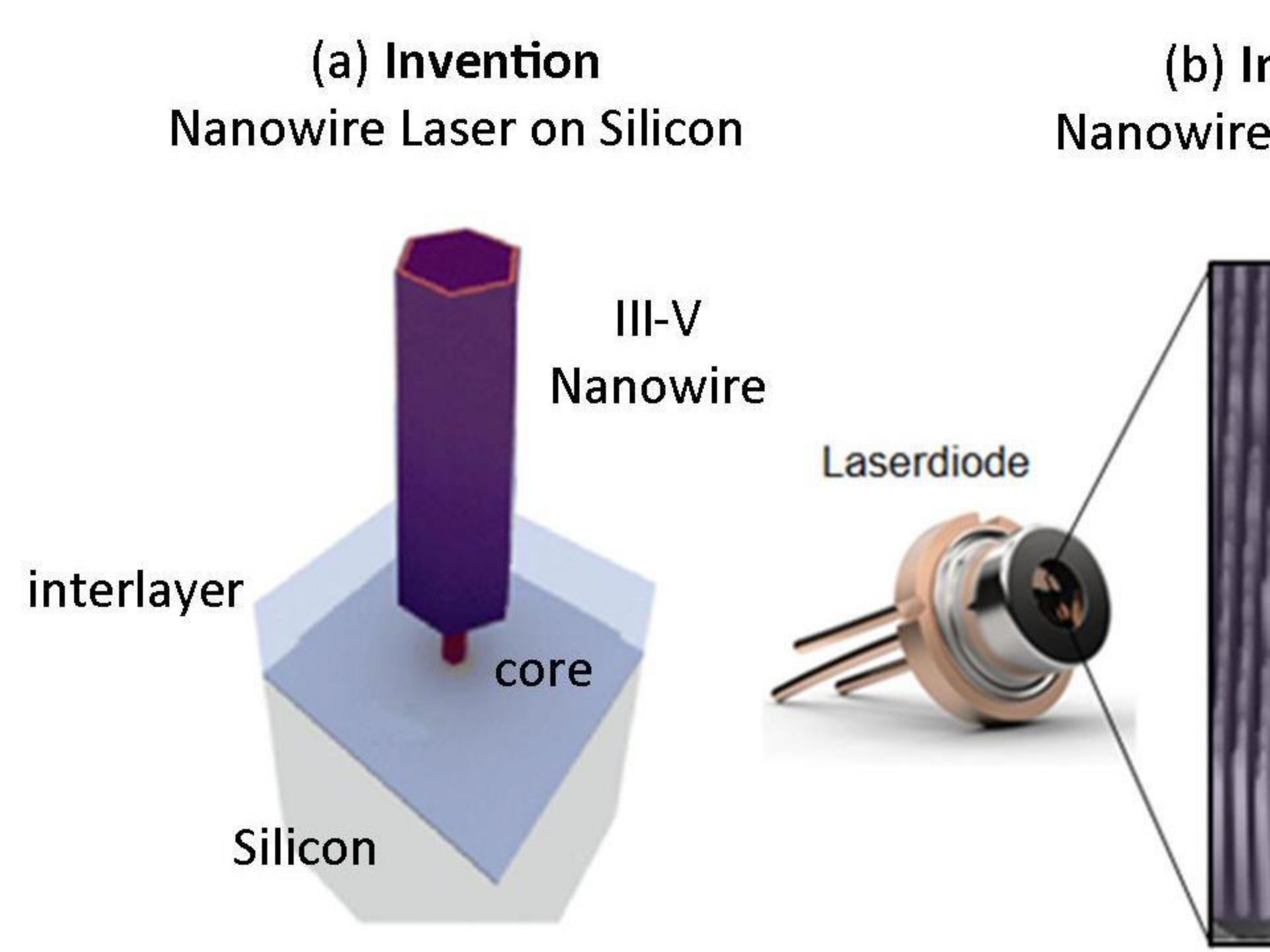
Wikipedia : white LED

Laser Diodes: AlGaN nanowire laser diode emits at 239 nm

Over the years, the short-wavelength limit of laser diodes has moved from the red end of the visible spectrum to the near-UV.



https://www.laserfocusworld.com/lasers-sources/article/16546978/



(a) Invention
Nanowire Laser on Silicon
III-V
Nanowire
interlayer
core
Silicon
Laserdiode
(b)
Nanowire