EEE 6212
Semiconductor Materials

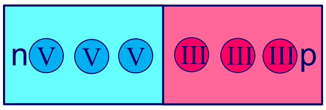
Lecture 21: pn-junctions and diodes

Lecture 21: pn-junction & diodes

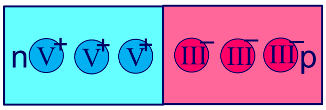
- formation of pn-junction
- solution of Poisson's equation for a pn-junction
- built-in electric field and bias
- electrical operation under forward/reverse bias
- diode characteristics
- types of diodes: rectifiers, LEDs, Zener diodes, RTDs
- principle of bipolar junction transistors (BJTs)

Formation of pn-junction

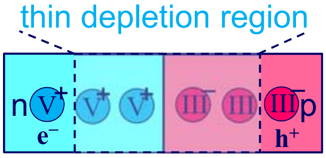
- contact two differently doped regions



- activate dopant atoms by annealing so they occupy lattice sites in tetrahedral coordination

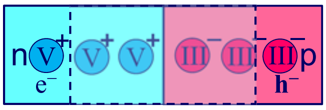


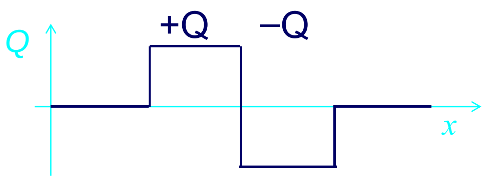
- mobile charge carriers diffuse across boundary, recombine and form a thin depletion region



Formation of pn-junction

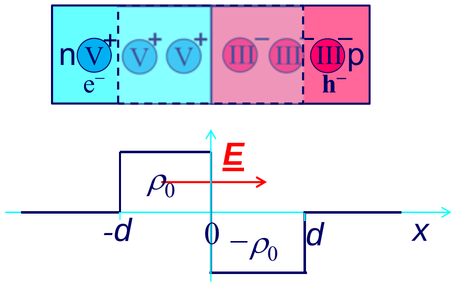
- ionised dopants create local charge density





- within the depletion, there are no free carriers any more: the depletion region is intrinsic and does **not** conduct

Poisson equation for pn-junction

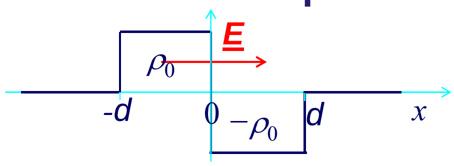


- consider step function of charge density:

$$\rho = \begin{cases} +\rho_0 \text{ for } -d<x<0, \\ -\rho_0 \text{ for } 0<x<d \end{cases}$$

- solve Poisson equation $\nabla^2 V$ = div grad V = – div $\underline{\mathbf{E}} = -\rho/\varepsilon$

Poisson equation for pn-junction



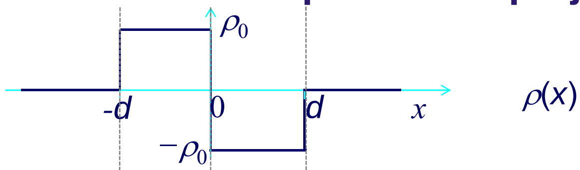
- solve Poisson equation in 1D (x-direction): $\partial^2 V/\partial x^2 = -\rho_0/\varepsilon$ for left (*n*) side
- double integration yields equation with 3 constants: $V(x)=c_1x^2+c_2x+c_3$
- then: $-E(x)=\partial V/\partial x=2c_1x+c_2$ and $\partial^2 V/\partial x^2 = 2c_1$ -> $c_1=-\rho_0/(2\varepsilon)$
- boundary condition: @ $x=0$: $V(0)=0$ -> $c_3=0$

  @ $x=-d$: $E(-d)=0$ -> $-2c_1(-d)-c_2=0$

  -> $c_2=-\rho_0 d/\varepsilon$

-> $V(x<0)=-\rho_0/(2\varepsilon)\,x^2-\rho_0 d/\varepsilon\, x = -\rho_0/(2\varepsilon)\,(x^2+2dx)$

Poisson equation for pn-junction

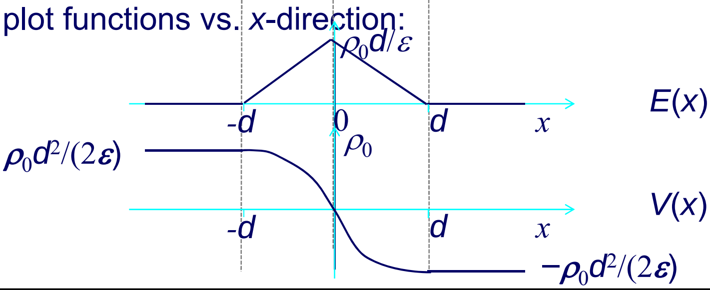


- put solutions for both sides together:

  $V(x<0) = -\rho_0/(2\varepsilon)\,(x^2+2dx)$, in particular: $V(-d) = \rho_0 d^2/(2\varepsilon)$

  $V(x>0) = +\rho_0/(2\varepsilon)\,(x^2-2dx)$, in particular: $V(d) = -\rho_0 d^2/(2\varepsilon)$

- plot functions vs. x-direction:



built-in potential and electric field

- some typical numbers:
- Si, ε_r=11, doping of 1ppm, 2/3 of dopants activated, d=90nm
- ρ_0 = 2/3 *10^{-6} *ne = 2/3 * 10^{-6} * $8/a^3$ *e = 5335 C/m^3
- $\varepsilon = \varepsilon_0 \varepsilon_r$= 8.8542 * 10^{-12} As/(Vm) *11
- $E_{max} = \rho_0 d/\varepsilon$ =5.5 * 10^6 V/m
- $V_{b\text{-}i} = V(-d) - V(d) = \rho_0 d^2/\varepsilon$ = 0.55 V

  This is the built-in potential across the pn-junction.

  For the diode to conduct, the applied voltage (bias) needs to at least compensate this built-in potential.

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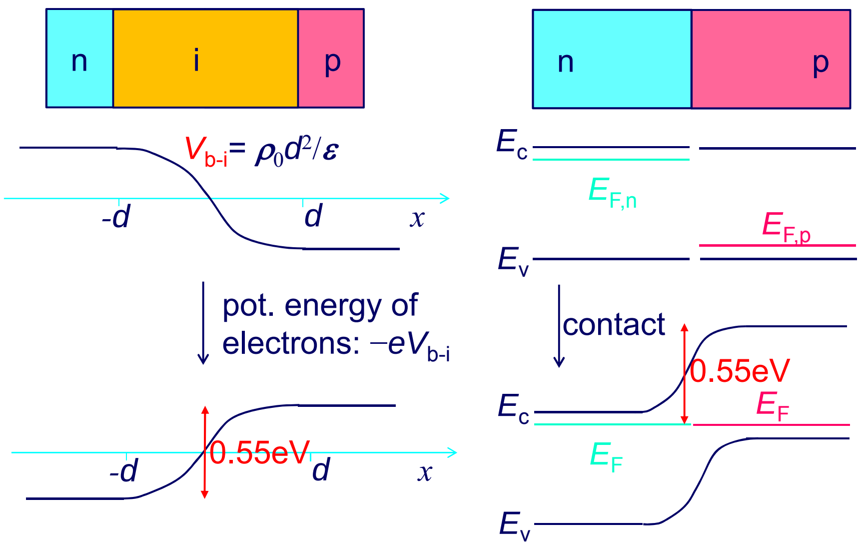
built-in potential and Fermi-level



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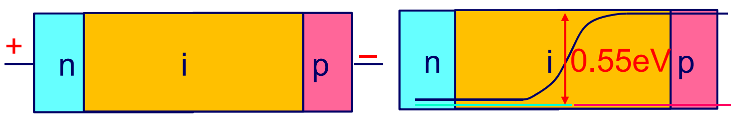
qualitative diode behaviour

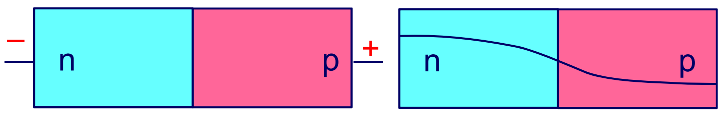
reverse bias: diode blocks



depletion region expands

$V_{bias} < V_{b\text{-}I}$ or even enhances $V_{b\text{-}i}$

forward bias: diode conducts



depletion region shrinks and finally vanishes

$V_{bias} > V_{b\text{-}I}$ counter-acts $V_{b\text{-}i}$

quantitative diode behaviour

- thermodynamic calculation of built-in potential: consider current densities due to both drift and diffusion on both sides:

  $j_n = ne\mu_e E + eD_n\, \partial n(x)/\partial x$ $\qquad$ $j_p = pe\mu_p E - eD_p\, \partial p(x)/\partial x$

- in equilibrium, there is no charge motion any more: $j_n = j_p = 0$

  -> $E = -D_n/(n\mu_e)\, \partial n(x)/\partial x$ $\qquad$ $E = D_p/(p\mu_p)\, \partial p(x)/\partial x$

  -> $V_{b\text{-}i} = -\int_{-d}^{d} E_x\, dx = -\int_{-d}^{d} -[D_n/(n\mu_e)\, \partial n(x)/\partial x]\, dx = D_n/\mu_e \int_{n_p}^{n_n} 1/n\, dn(x)$

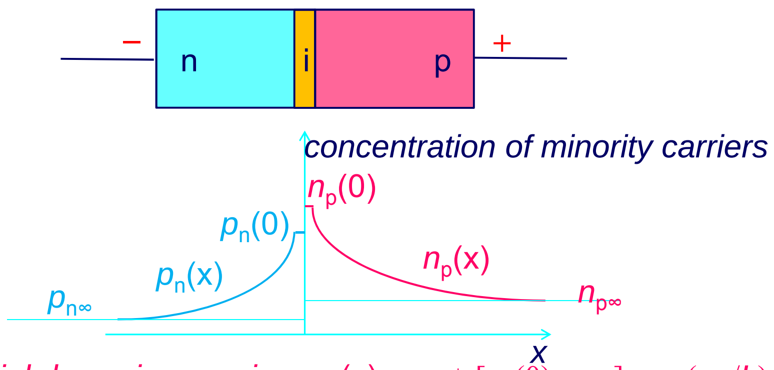
  $= D_n/\mu_e\, \ln(n_n/n_p)$

  $\approx kT/e\, \ln(N_D N_A/n_i^2)$

For silicon with $N_A = N_D = 5*10^{15}$ cm^{-3}, $n_i = p_i \approx 10^{10}$ cm^{-3}, room temp.:

$V_{b\text{-}i} \approx 0.026\text{V}\, \ln(25*10^{10}) \approx$ 0.68V

diode characteristics



exponential decay in p–region: $n_p(x) = n_{p\infty} + [n_p(0) - n_{p\infty}]\exp(-x/L)$

exponential decay in n–region: $p_n(x) = p_{n\infty} + [p_n(0) - p_{n\infty}]\exp(x/L)$

approximations: applied voltage (bias)drops almost exclusively across depletion region and Maxwell-Boltzmann distribution

$n_n/n_p = p_p/p_n = \exp[eV_{b\text{-}i}/(kT)]$ is valid

diode characteristics

exponential decay in p-region: $n_p(x)=n_{p\infty}+[n_p(0)-n_{p\infty}]\exp(-x/L_n)$
exponential decay in n-region: $p_n(x)=p_{n\infty}+[p_n(0)-p_{n\infty}]\exp(x/L_p)$

approximations: applied voltage (bias)drops almost exclusively across depletion region and Maxwell-Boltzmann distribution

$n_n/n_p = p_p/p_n = \exp[eV_{b\text{-}i}/(kT)]$ is valid

-> $n_n = n_p \exp[eV_{b\text{-}i}/(kT)] \approx n_p(0)\exp(-x/L)\exp[eV_{b\text{-}i}/(kT)]$

$\approx n_p(0)\exp[e(V_{b\text{-}i}-V_d)/(kT)]$ where V_d is the applied bias

-> diffusion currents in depletion region:

$j_n|_{x=0} = eD_n\, \partial n_p/\partial x|_{x=0} = eD_n\, n_p(0)/L_n\, [\exp(eV_d/(kT)-1]$

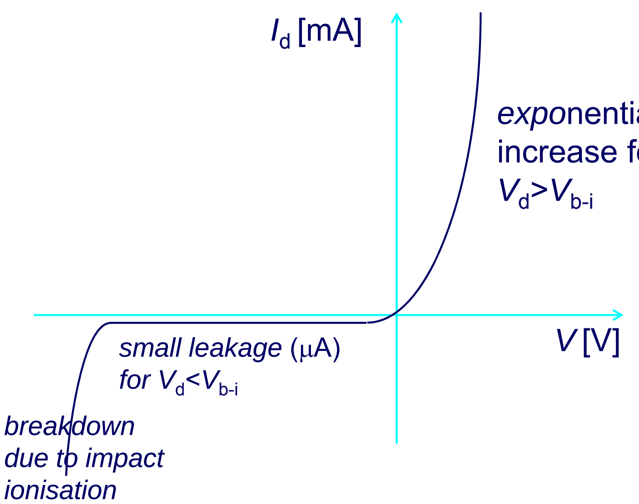
$j_p|_{x=0} = -eD_p\, \partial p_n/\partial x|_{x=0} = eD_p\, p_n(0)/L_p\, [\exp(eV_d/(kT)-1]$

-> total diode current through area A is $I_d=A(j_n+j_p)$, hence

$I_d=I_S[\exp(eV_d/(kT)-1]$ where $I_S=eA[D_p\, p_n(0)/L_p+D_n\, n_p(0)/L_n]$

diode characteristics

$I_d=I_S[\exp(eV_d/(kT)-1]$ is known as Shockley's diode equation.



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types of diodes and applications

- rectifying diode: blocks for $V<V_{b\text{-}i}$ and conducts for $V>V_{b\text{-}i}$
- biasing diode: yields voltage drop of $V_{b\text{-}I}$ (~0.6V for silicon)
- LEDs: light-emitting diodes when a direct band-gap semiconductor pn-junction is forward biased with $eV>E_g$ so electrons and holes are injected from opposite ends and recombine near the contact area, creating photons (light)
- Zener diodes: reverse biased, yield constant voltage drop independent of current flow
- APDs: avalanche photodiodes are operated under very strong reverse bias (so normally only leakage current); if a high-energy photon or X-ray strikes, it produces e-h pairs that can be separated in the field and due to their high energy produce an avalanche of further charge carriers (-> high current pulse)

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principle of bipolar junction transistor (BJT)

principle: connect 2 diodes with same doping back-to-back so you get a 3-terminal device and operate one diode just under forward bias (base-emitter, BE) and the other under reverse bias (base-collector, BC)

npn: V_{BE}~0.7V, V_{CB}>>1V   pnp: V_{BE}~–0.7V, V_{CB}<< –1V