Section 14
Doping

Gerhard Klimeck

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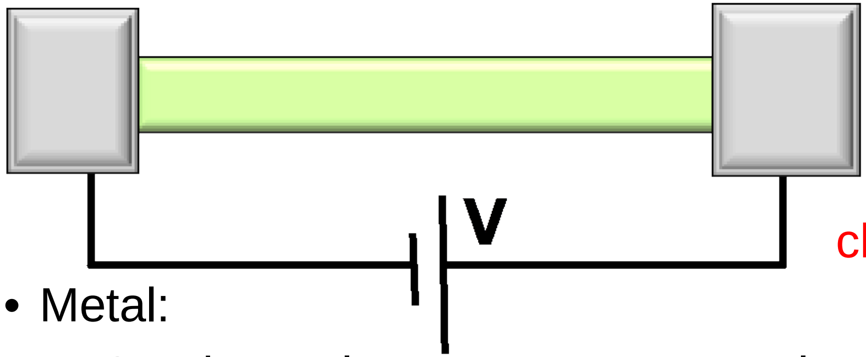
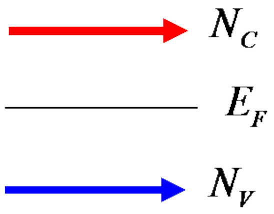
School of Electrical and Computer Engineering



$I = G \times V$

$= q \times n \times v \times A$

charge density velocity area



- Metal:
  - » Conducts electrons even at very low temperatures
- Semiconductor
  - » Ge: Eg=0.8eV n_i~$10^{13}/cm^3$ 0.1 in a billion
  - » Si: Eg=1.1eV n_i~$10^{10}/cm^3$ 0.1 in a trillion
  - » GaAs: Eg=1.42eV n_i~$10^{6}/cm^3$ 1 in 10^{17}
  - » Very weakly conducting

Not Enough Electrons available

- **Materials, composition, crystals**
- Tabulated for **"known" bulk materials**
- At nm-scale properties change with geometry => theory

⇒ Quantum Mechanics Mechanics

- Concepts of **density of states and masses**

⇒ Equilibrium Statistical Mechanics

- **Occupation factors**

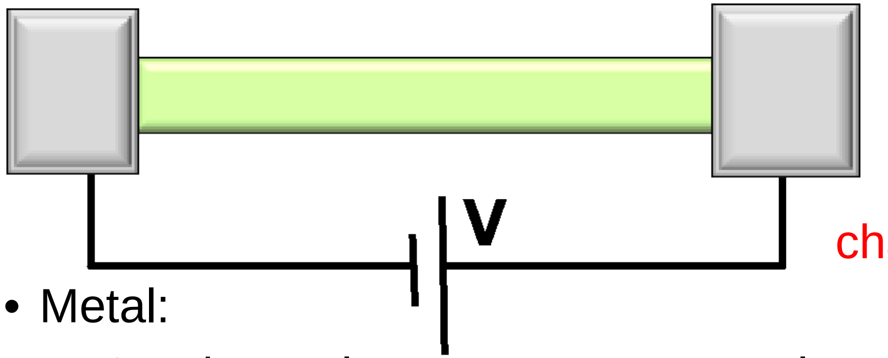
Transport with scattering, non-equilibrium Stat. Mech.

- Drift-diffusion equation with recombination-generation

... transport in concrete devices

- Diodes, BJT/HBT, MOS

Doping



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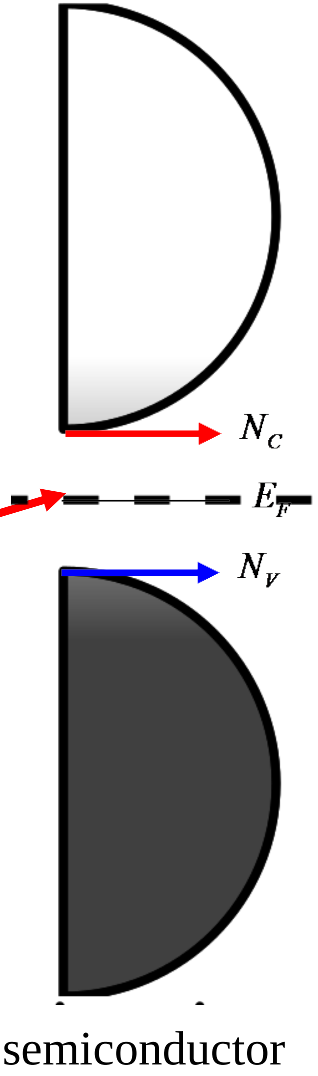
  - » Fermi level about midgap – no DOS



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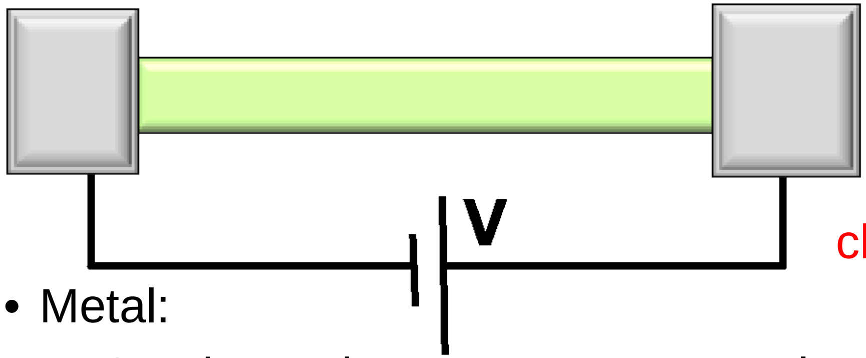

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- Metal:
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  - » Fermi Level crosses multiple bands
    => large density of states at Fermi level
- Semiconductor

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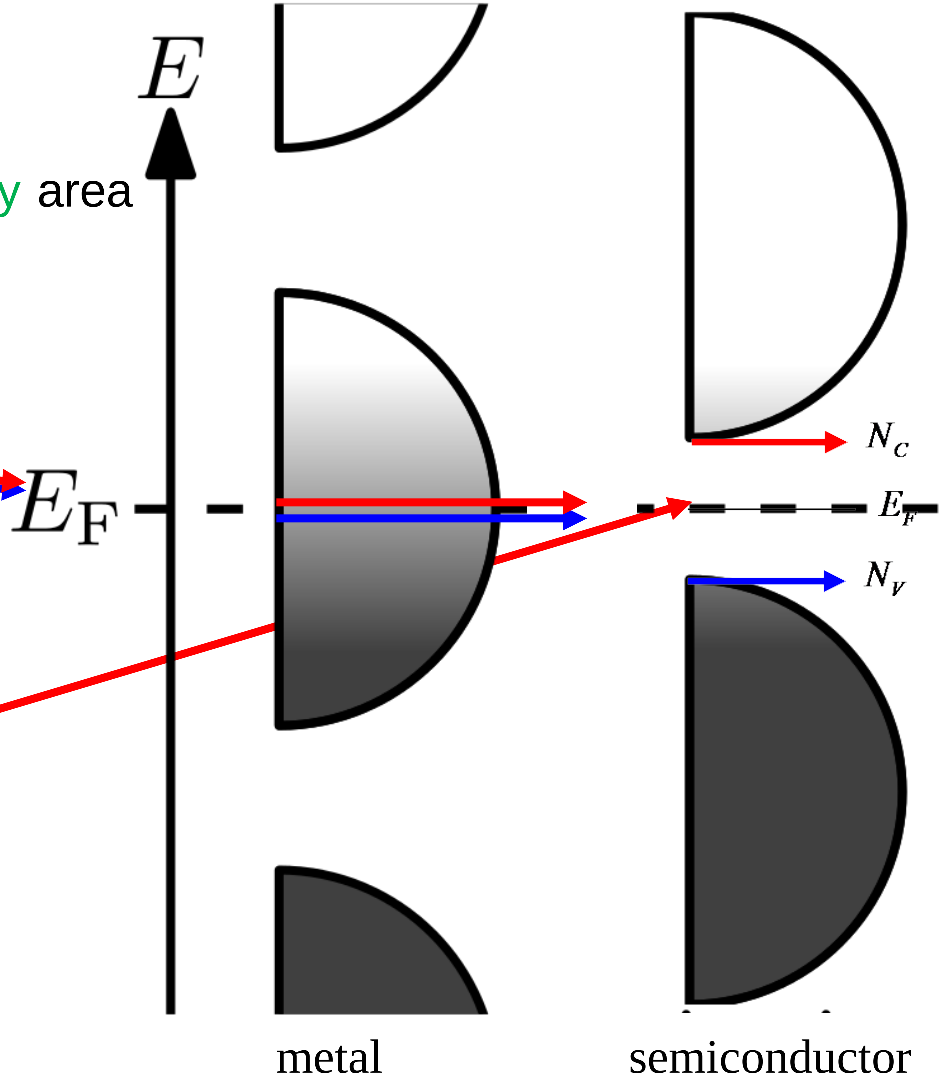

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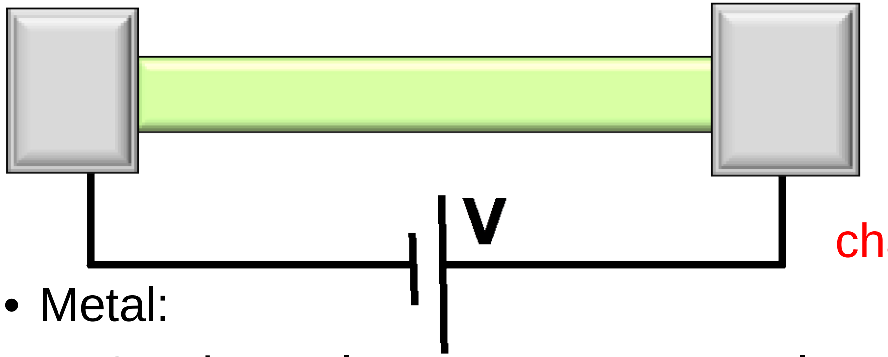

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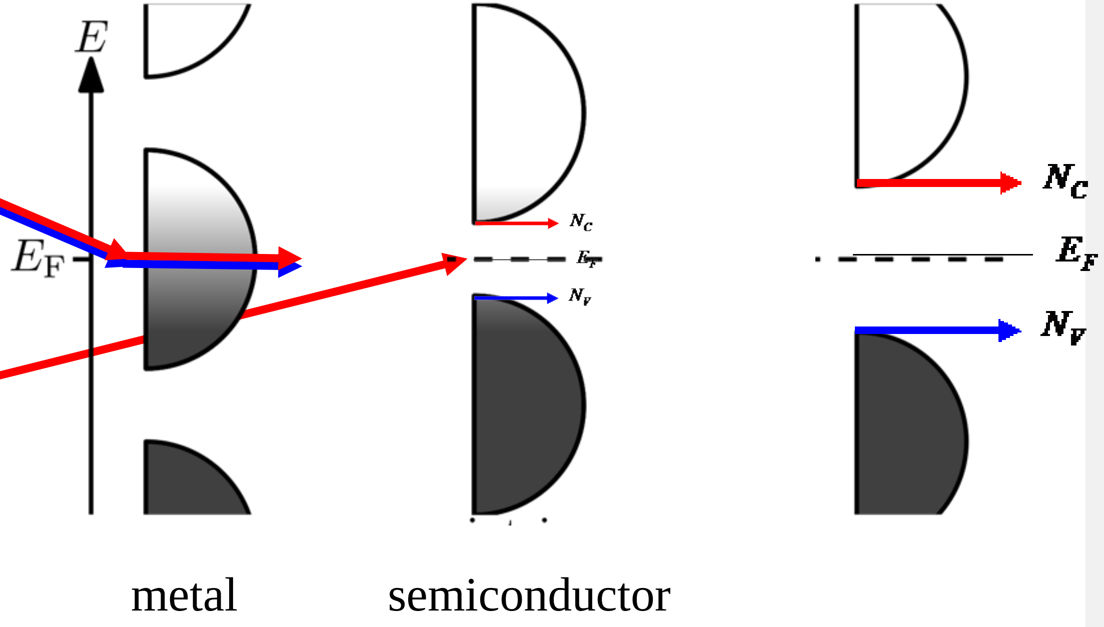
  - » Very weakly conducting
  - » Fermi level about midgap – no DOS
- Insulator
  - » “Not” conducting – Fermi level midgap
  - » SiO_2, E_g= 9eV, $n_i \sim 10^{-68}/cm3$
    - ✓ The whole earth has about 10^{50} atoms! If you made the whole world out of glass, there would be not one electron conductive at room temperature!



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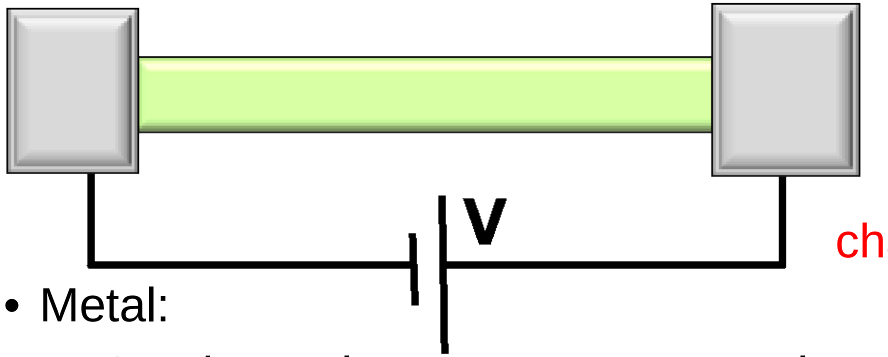

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charge density velocity area

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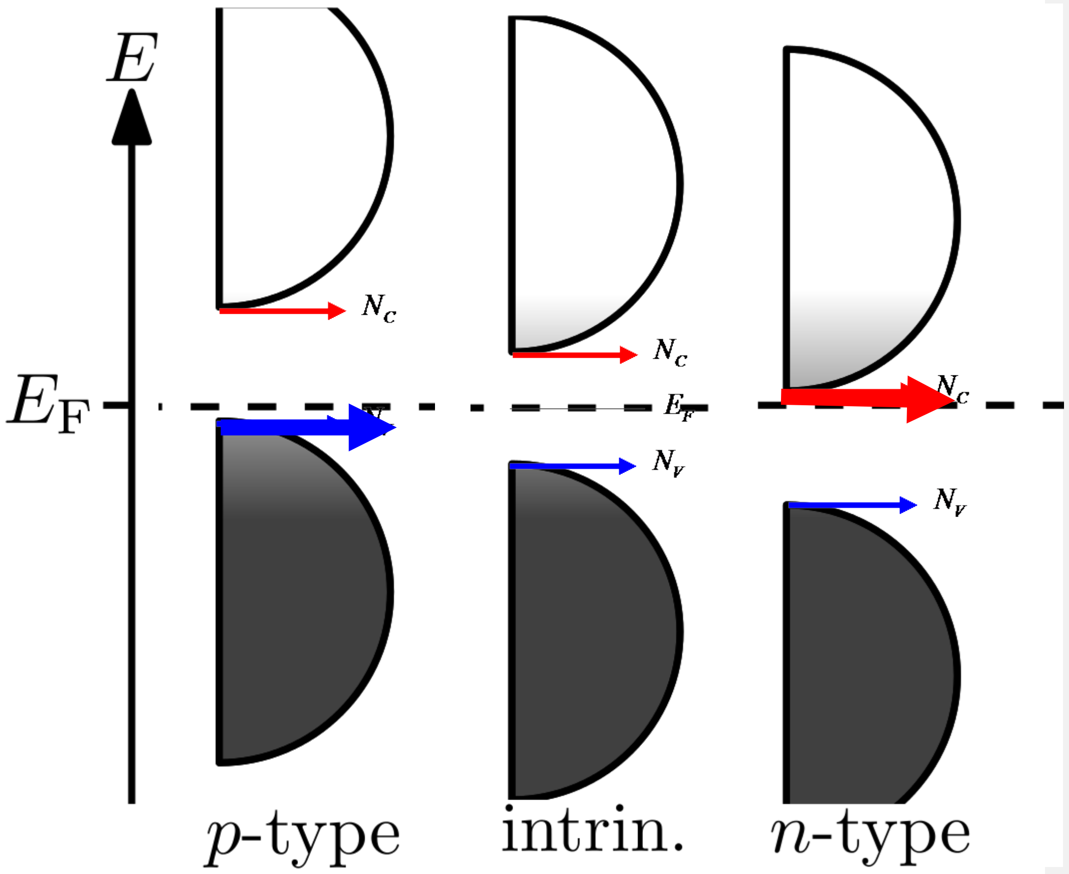
  - » Very weakly conducting
  - » Fermi level about midgap – no DOS
  - » Need to "move" the Fermi level
  - » "add" electrons – n-type doping – E_F close to E_c
  - » "add" holes – p-type doping – E_F close to E_v



semiconductor

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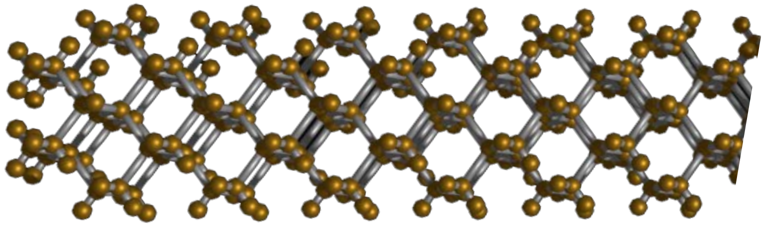


q x n

charge density

- **Materials, composition, crystals**
- Tabulated for **"known" bulk materials**

Transport with scattering, non-equilibrium Stat. Mech.

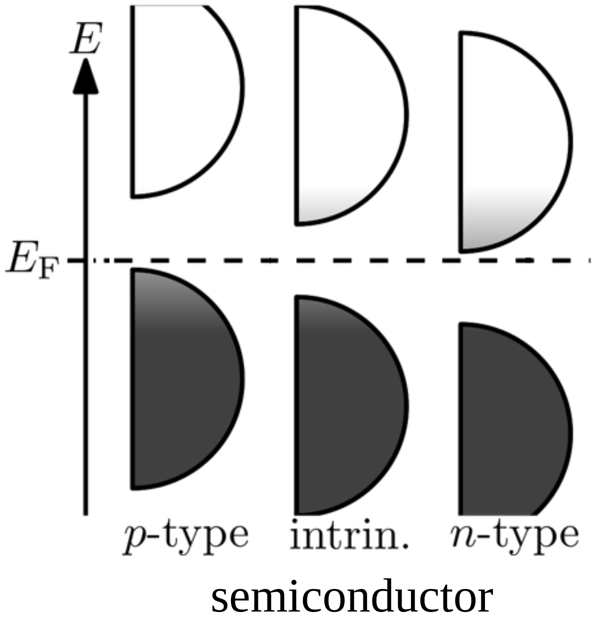
Video

Video

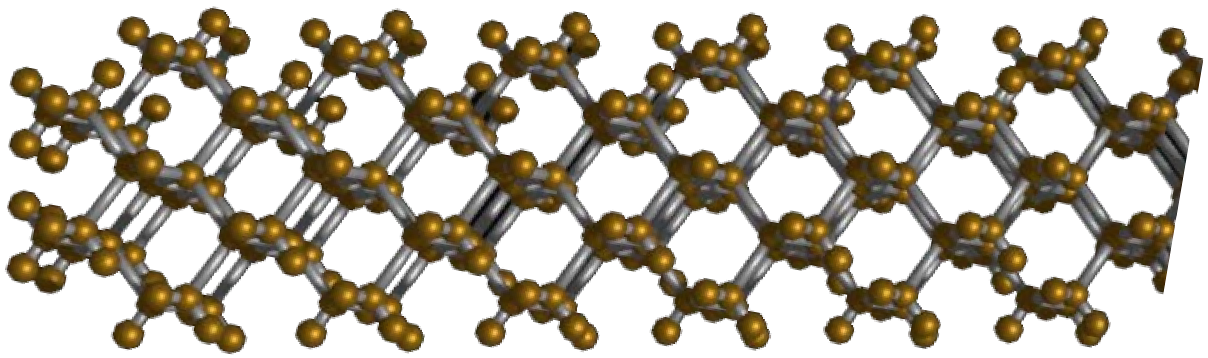
Video

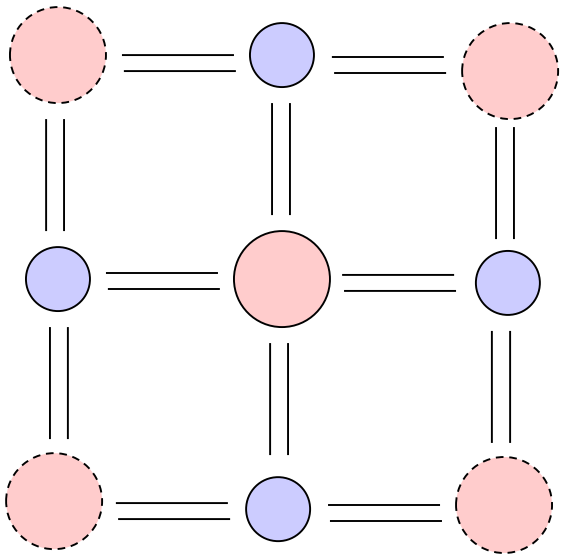
Video

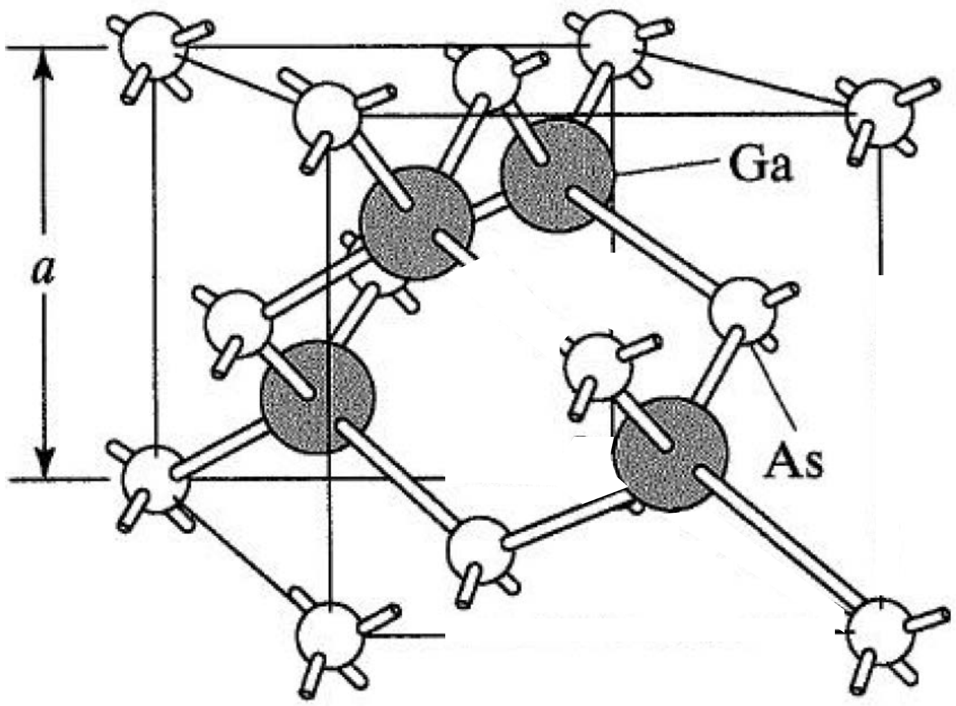
- 14.1 Basic concepts of donors and acceptors
  - » Need to "move" the Fermi level
  - » "add" electrons – n-type doping – E_F close to E_c
  - » "add" holes – p-type doping – E_F close to E_v
- 14.2 Statistics of donor and acceptor levels
- 14.3 Temperature dependence of carrier concentration
- 14.4 Multiple doping, co-doping, and heavy-doping



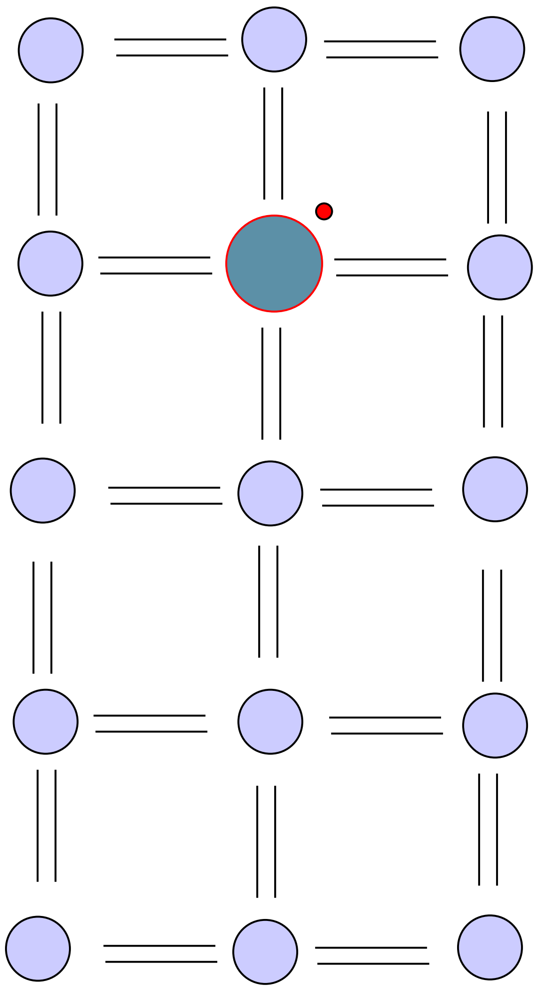
https://commons.wikimedia.org/wiki/File:Band_filling_diagram.svg






a
Ga
As

Donor Atoms



II	III	IV	V	VI
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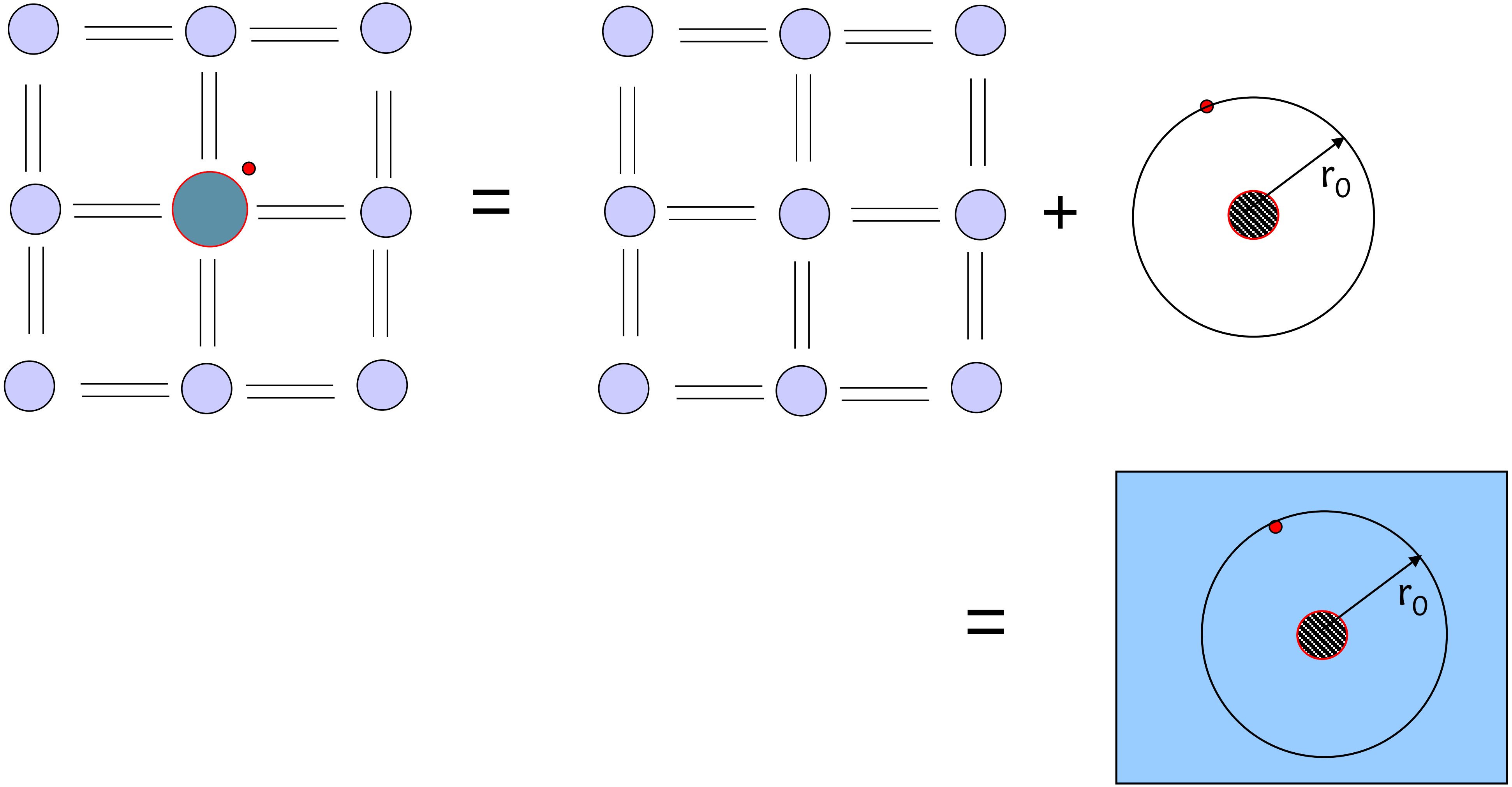
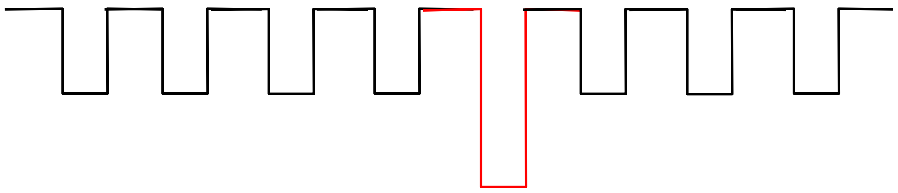
12 Mg	13 **Al**	14 **Si**	15 **P**	16 S
30 **Zn**	31 **Ga**	32 Ge	33 **As**	34 **Se**
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Even with donors, material is charge neutral

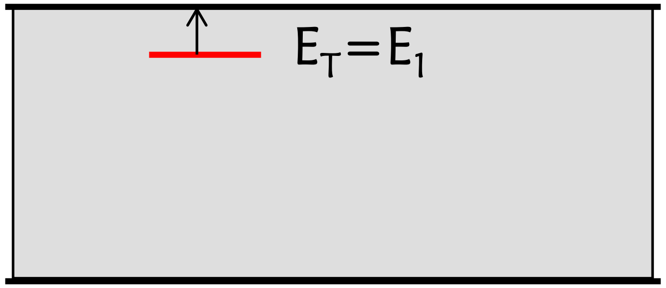
Donor Atoms in H2-analogy



Donor Atoms in Real and Energy Space



~10s meV

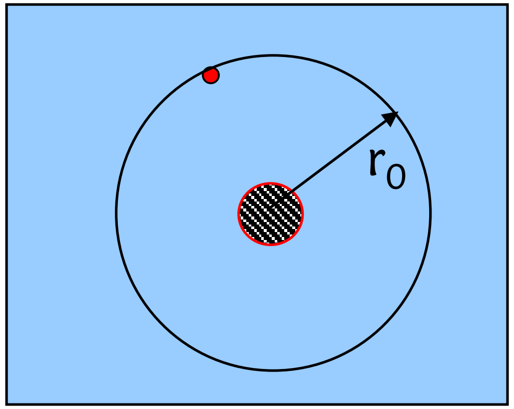


$1/\beta \sim k_B T \sim 25\,\text{meV}$ at T=300K

$$E_1 = -\frac{m^*_{host} q^4}{2\left(4\pi\varepsilon_0 K_{s,host}\hbar\right)^2}$$

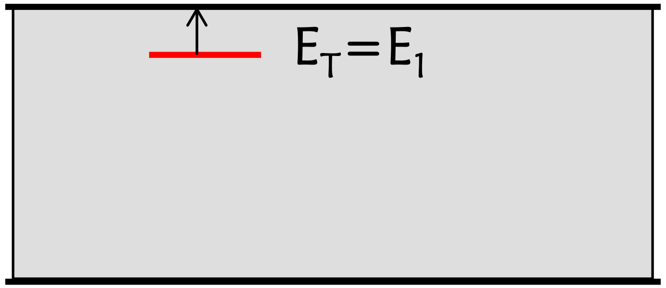
$$= -\frac{m_0 q^4}{2\left(4\pi\varepsilon_0\hbar\right)^2}\frac{m^*_{host}}{m_0}\frac{1}{K_{s,host}^2}$$

$$= -13.6 \times \frac{m^*_{host}}{m_0}\frac{1}{K_{s,host}^2}$$



Assumption of Large Radius ...

~10s meV



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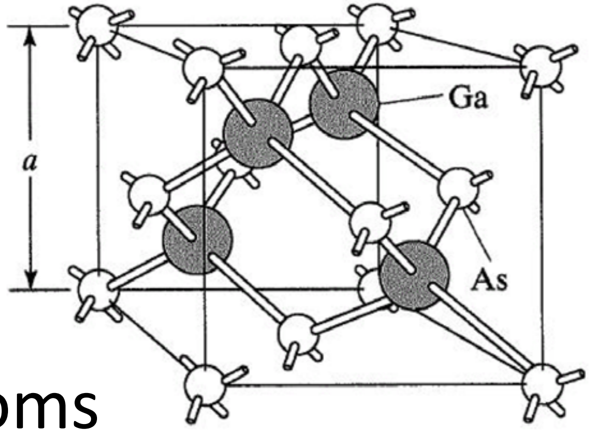
$$r_{1,P} = \frac{4\pi\varepsilon_0 K_{s,host}\hbar^2}{m^*_{host} q^2}$$

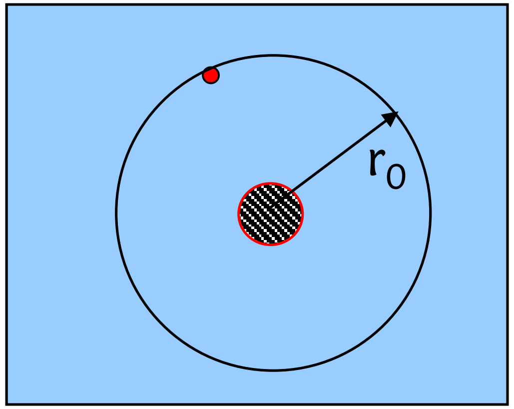
$$= \frac{4\pi\varepsilon_0 \hbar^2}{m_0 q^2} \frac{m_0 K_{s,host}}{m^*_{host}}$$

$$= r_{1,H} \frac{K_{s,host}}{m^*_{host} / m_0}$$

$$r_{1,P} = 0.53\ A \times \frac{12.9}{0.53} = 12.9\ A$$

a~0.5nm=5A => hundreds of Si atoms





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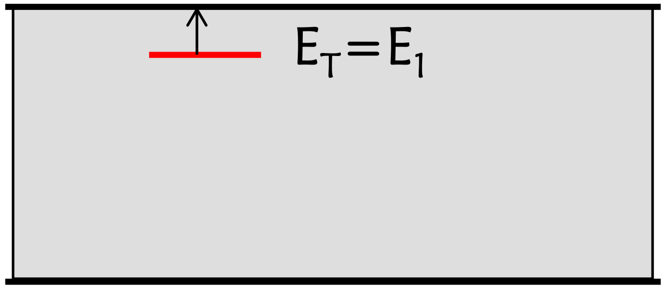

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Gate-induced quantum-confinement transition of a single dopant atom in a silicon FinFET

G. P. LANSBERGEN[1]*, R. RAHMAN[2], C. J. WELLARD[3], I. WOO[2], J. CARO[1], N. COLLAERT[4], S. BIESEMANS[4], G. KLIMECK[2,5], L. C. L. HOLLENBERG[3] AND S. ROGGE[1]

Published online: 15 June 2008; doi:10.1038/nphys994

Single Impurity / Donor in a modern FinFET

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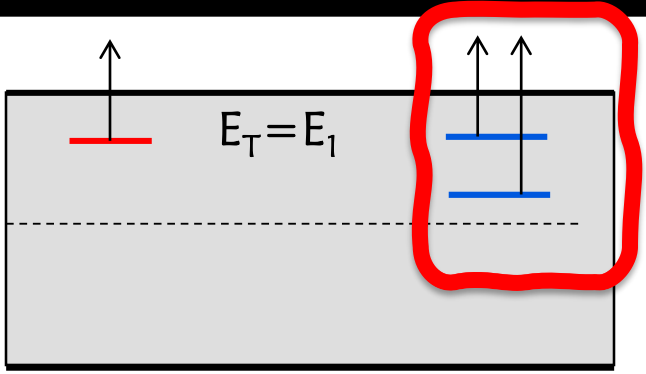

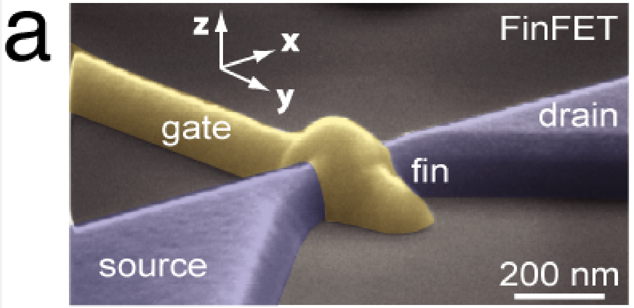

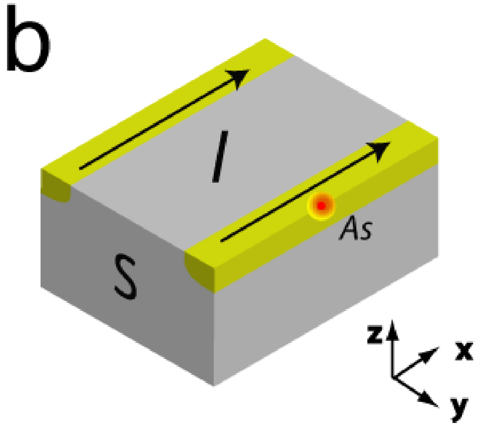

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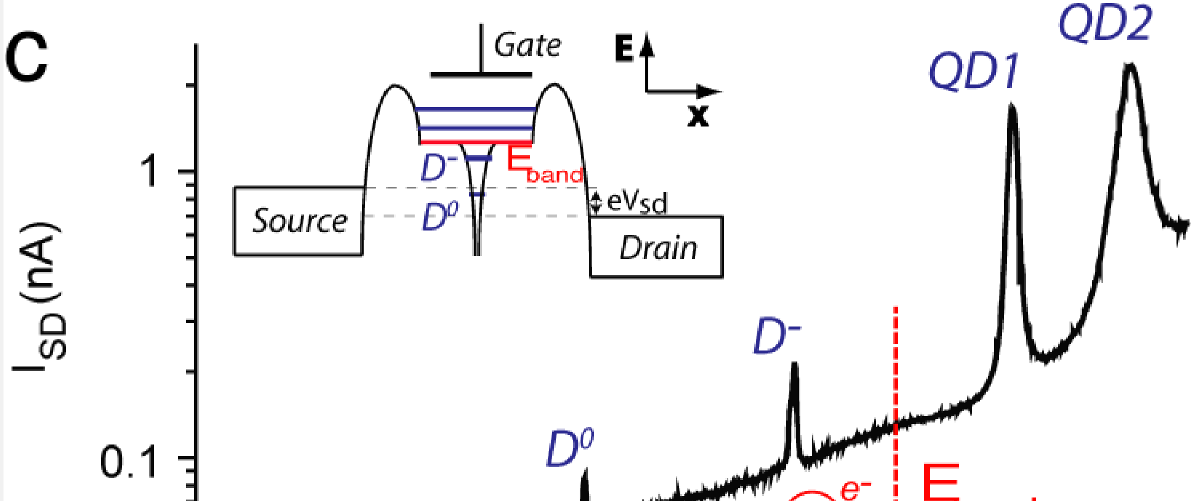

15 June 2008; nature physics

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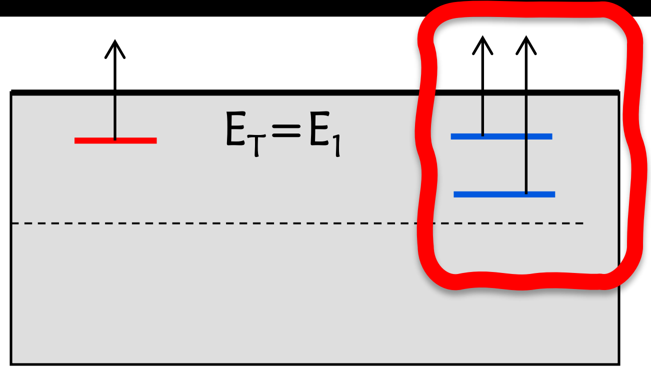
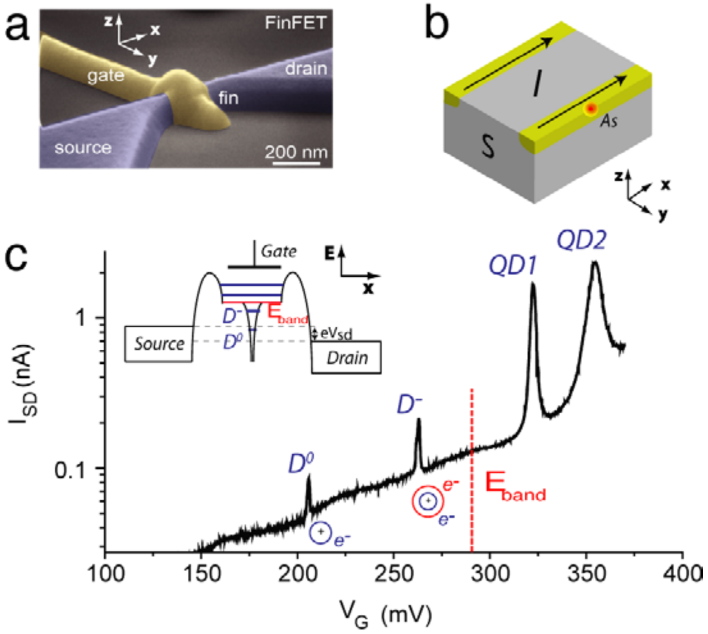
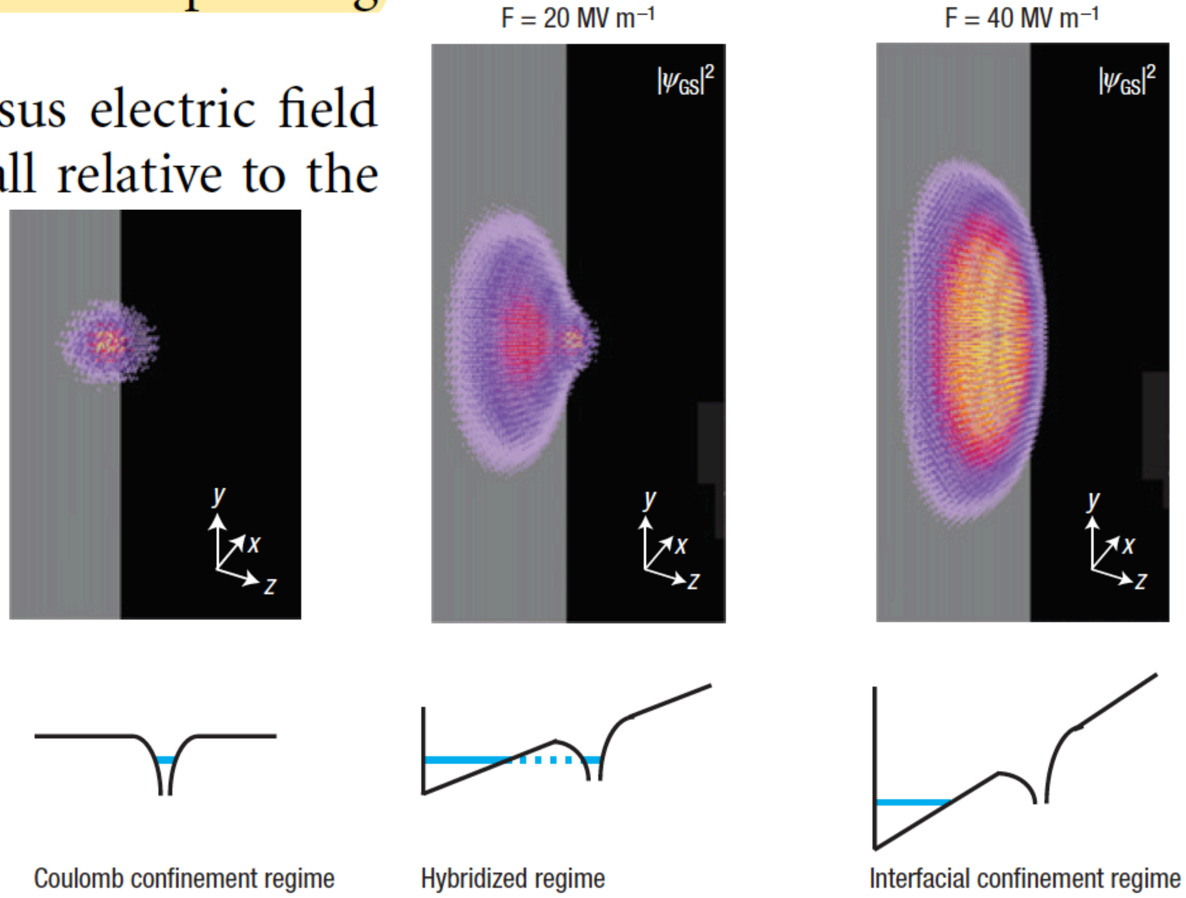
give an excellent account of the essential physics of the gated donor system. The calculations include 1.4 million atoms corresponding to device volumes $30.4 \times 30.4 \times 30.4$ nm.

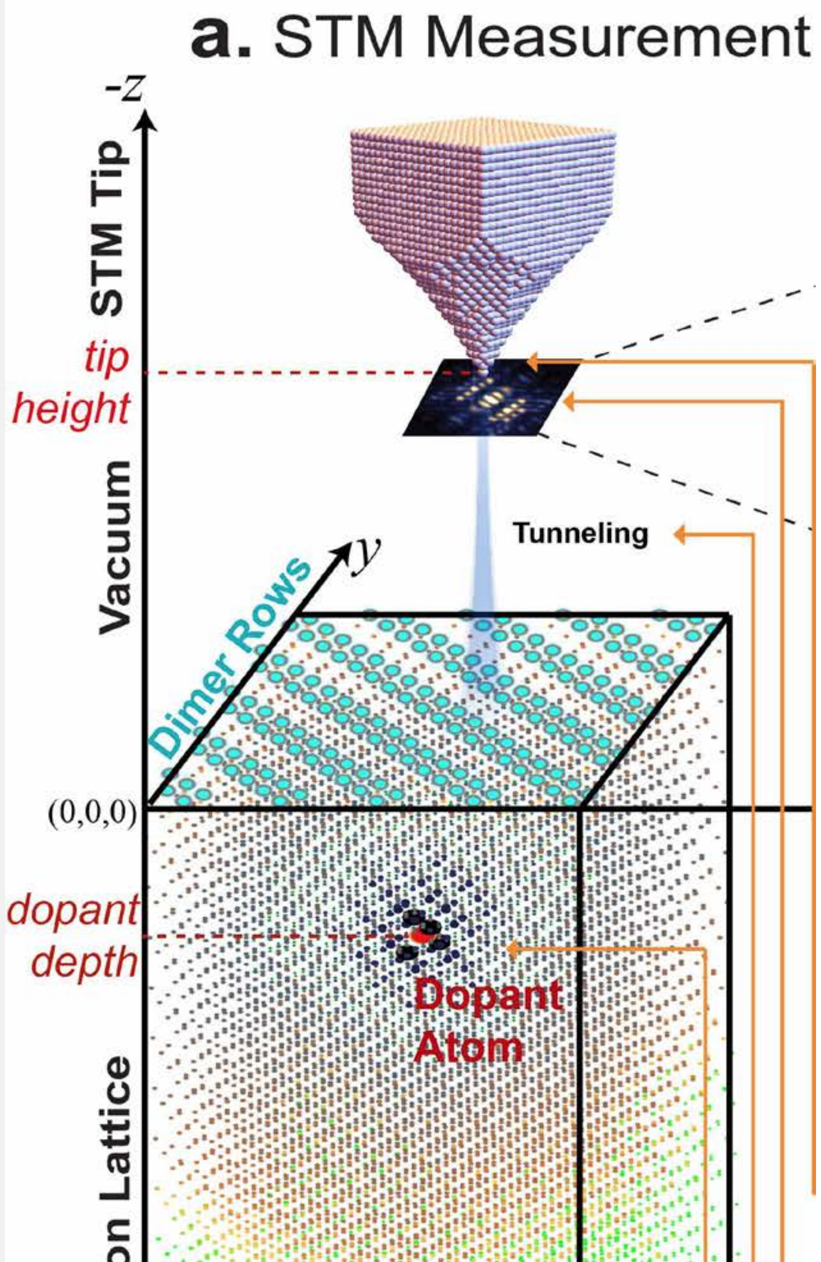
Figure 3 shows the first six eigenenergies versus electric field for $d = 15$ and 4.3 nm. The plotted energies are all relative to the

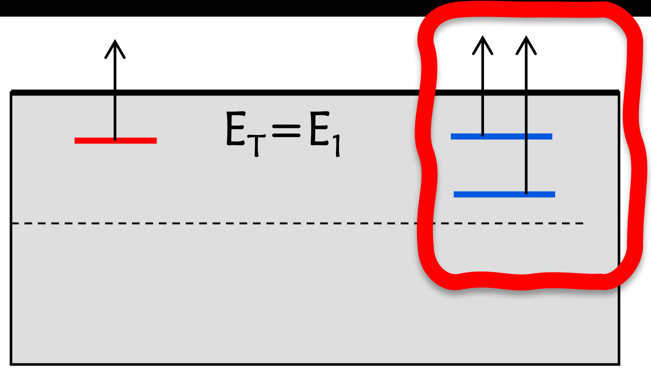






Measurement of Donor Wavefunctions

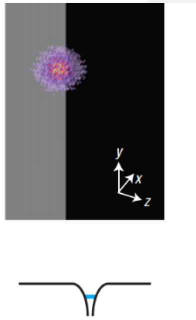




nature
nanotechnology

Spatial metrology of dopants in silicon with exact lattice site precision

M. Usman, J. Bocquel, J. Salfi, B. Voisin, A. Tankasala, R. Rahman, M. Y. Simmons, S. Rogge & L. C. L. Hollenberg



Usman, M., Bocquel, J., Salfi, J. et al. Spatial metrology of dopants in silicon with exact lattice site precision. Nature Nanotech 11, 763–768 (2016). https://doi.org/10.1038/nnano.2016.83

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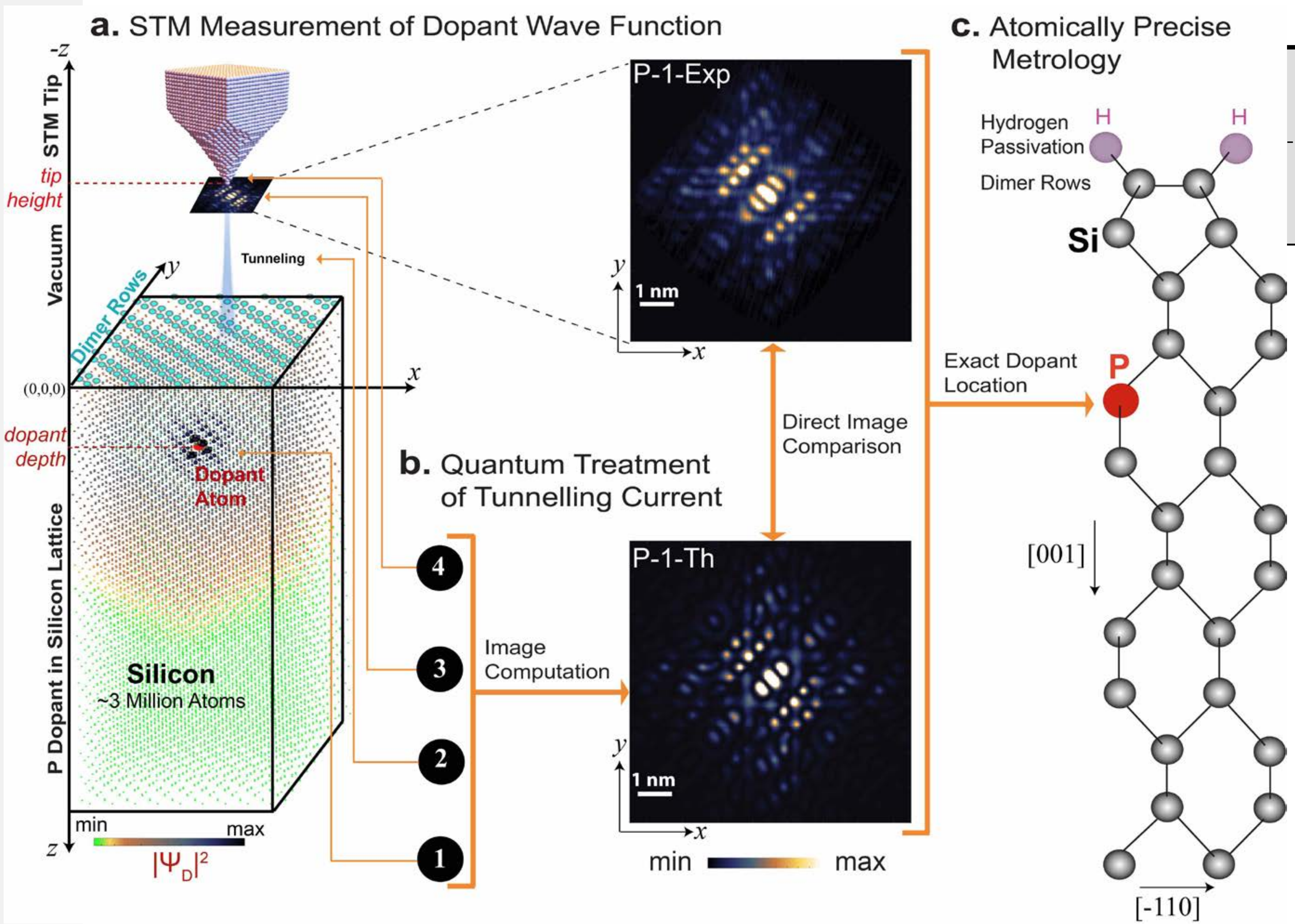

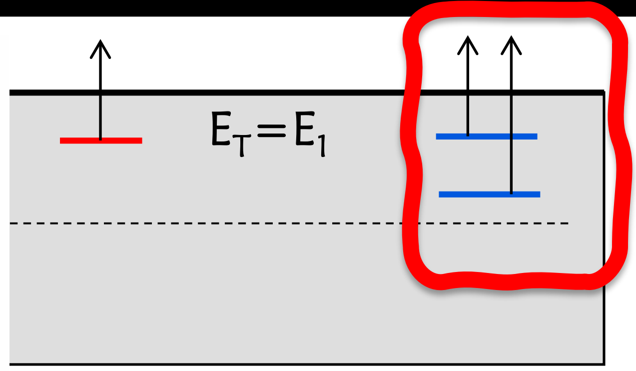

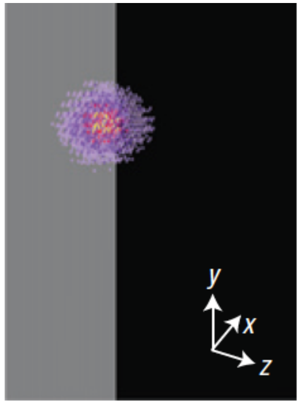

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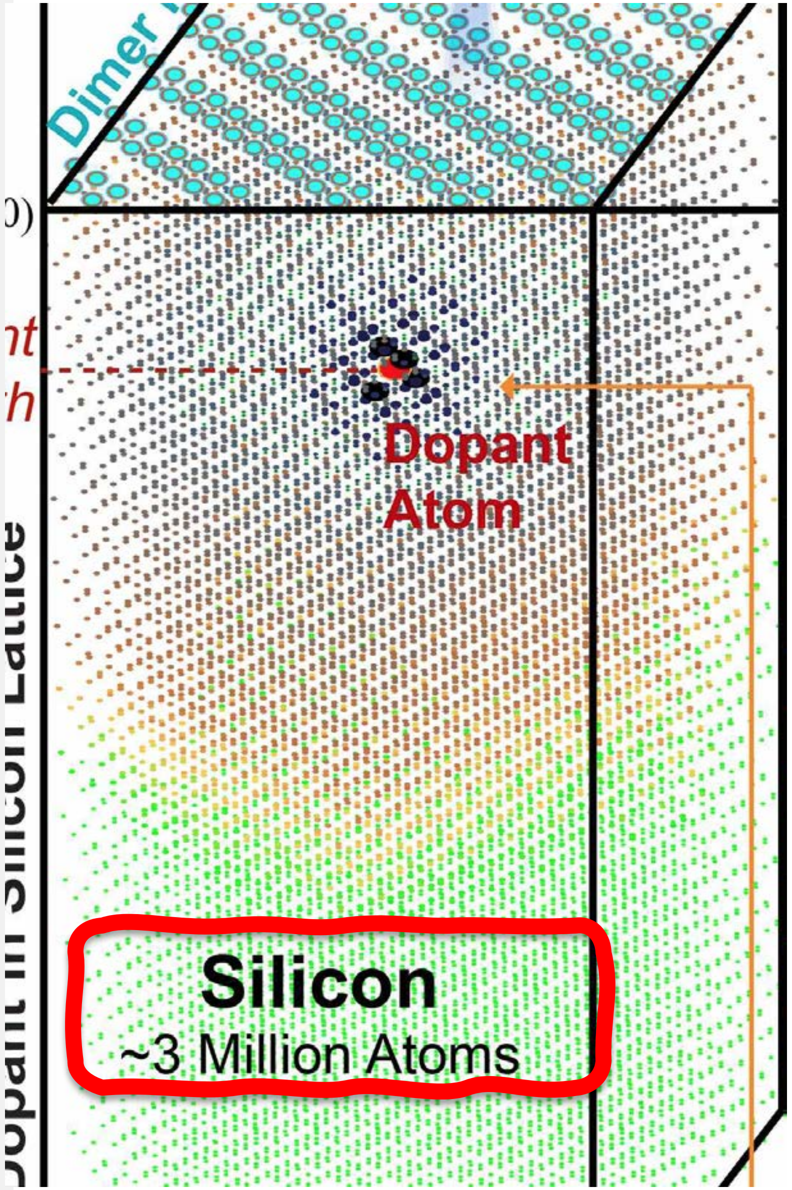

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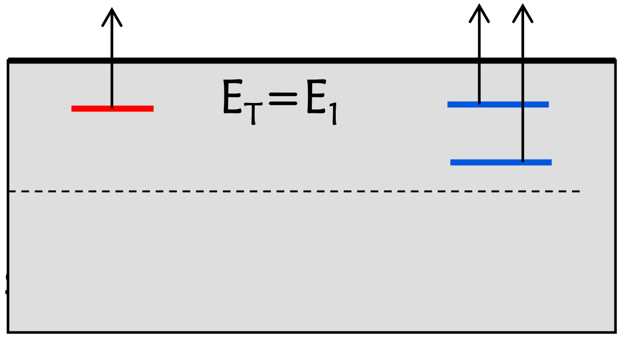
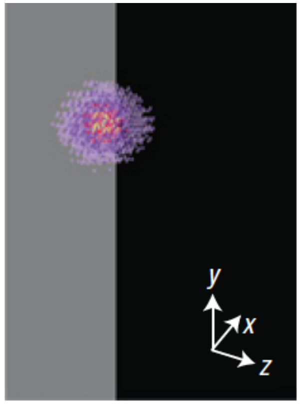
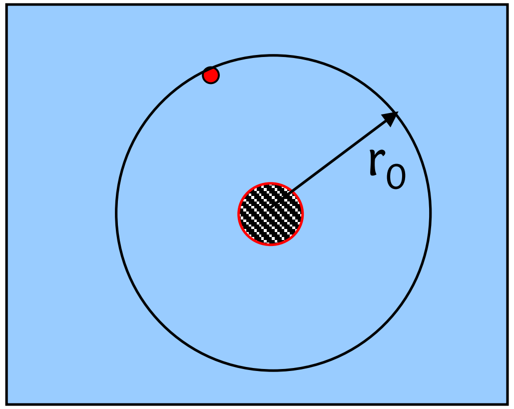


nature nanotechnology





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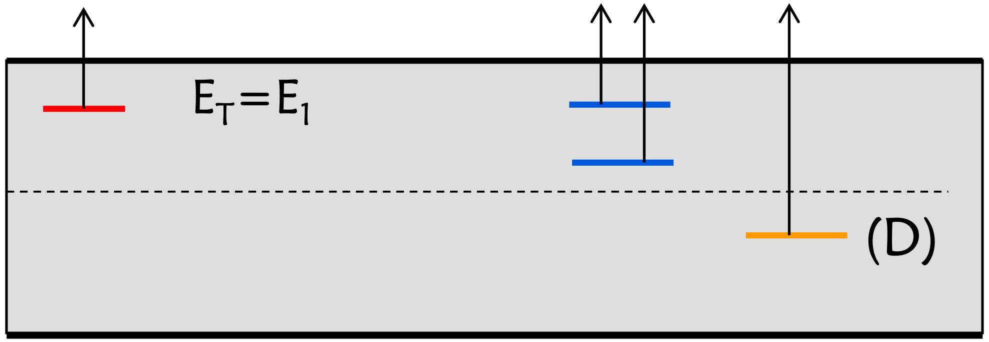
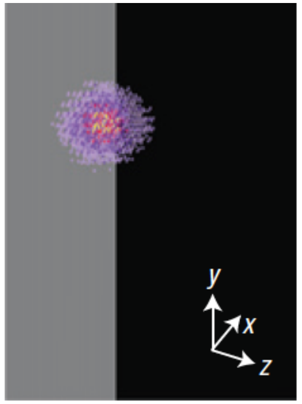
Characteristics of Donor Atoms

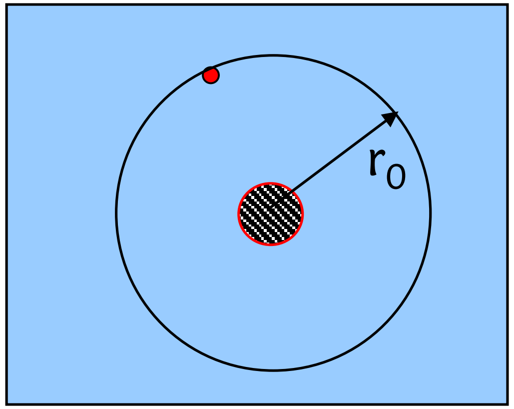
The number of donor atoms is much smaller compared to host atoms. Therefore, the electrons from one donor atom can go to the other donor atoms only via the conduction /valence bands of the host crystal.

Just like a Hydrogen atom, it is possible to have multiple localized level for a given atom (see the blue levels).

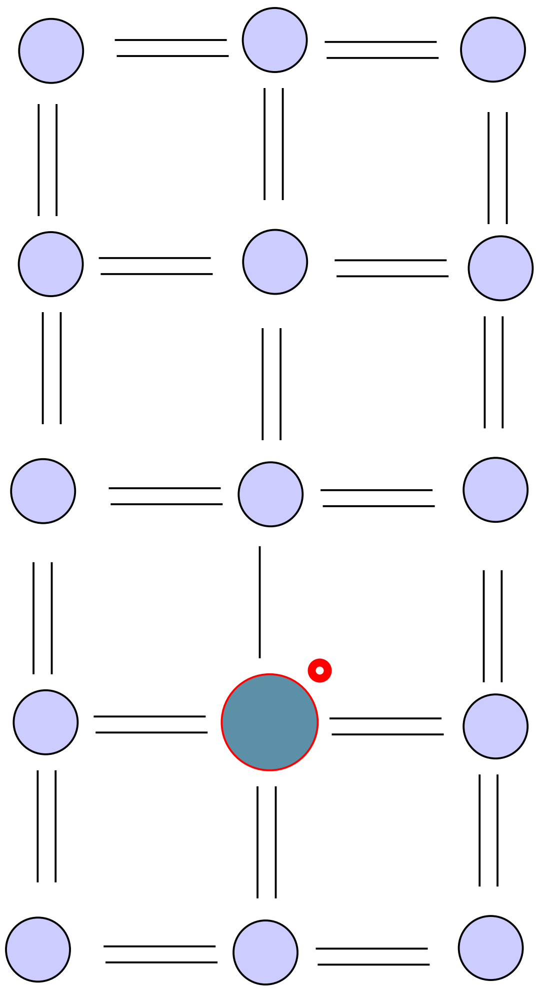
Good donors live close to the conduction band, so that they can offer electrons easily. However, if they are below the midgap, the donor levels are marked with (D) to differentiate them from acceptor atoms (which live close to the valence band).







Acceptor Atoms



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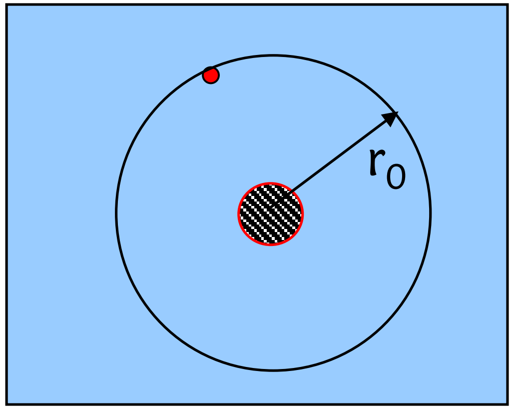
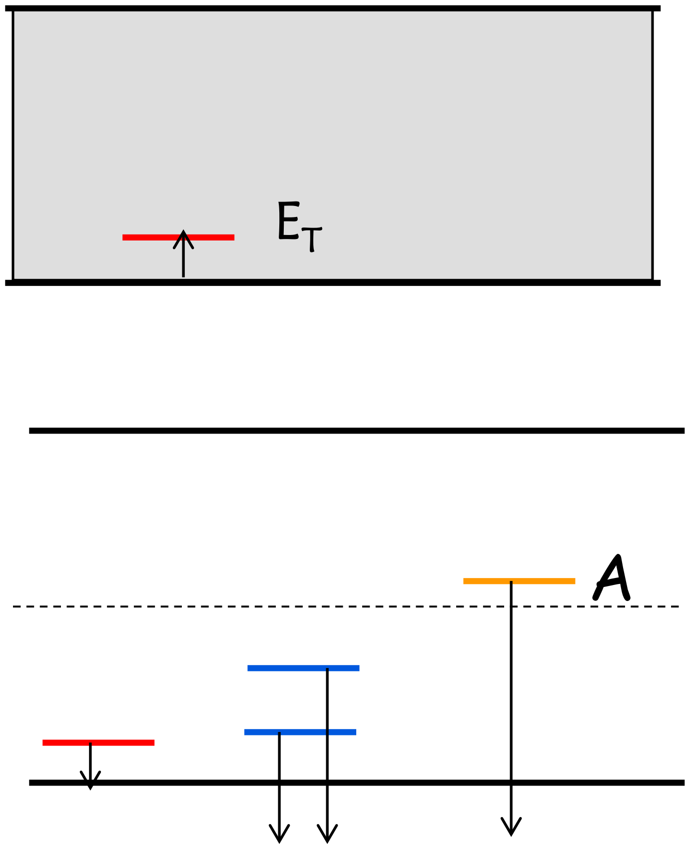
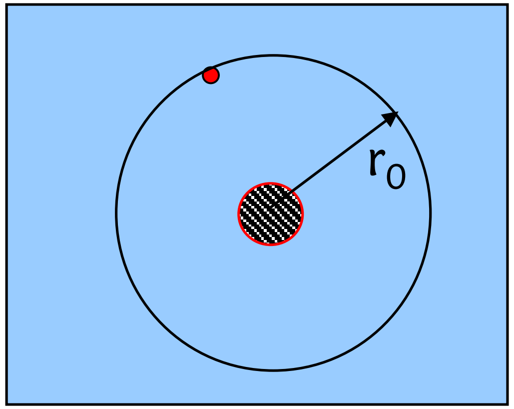
12 Mg	13 **Al**	14 **Si**	15 **P**	16 S
30 **Zn**	31 **Ga**	32 Ge	33 **As**	34 **Se**
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Even with acceptor, material is charge neutral




E$_T$
A


r$_0$

Amphoteric Dopants

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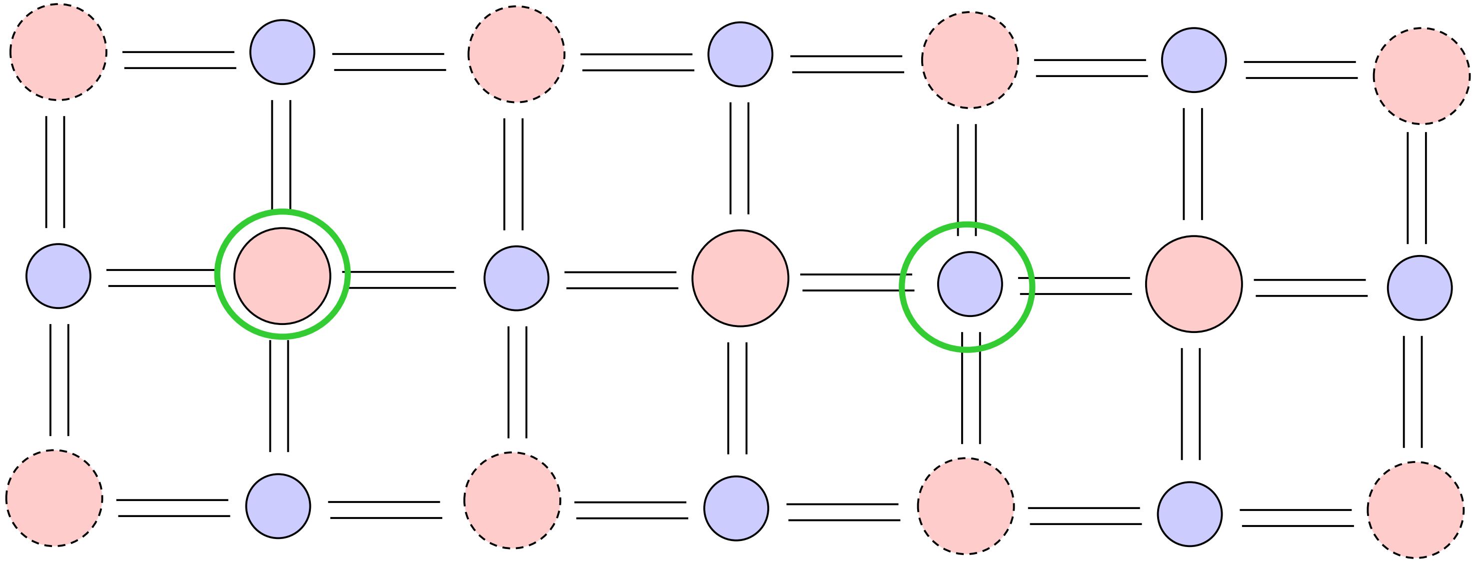
4 Be	5 B	6 C	7 N	8 O
12 Mg	13 **Al**	14 **Si**	15 **P**	16 S
30 **Zn**	31 **Ga**	32 Ge	33 **As**	34 **Se**
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Donor-type

acceptor-type



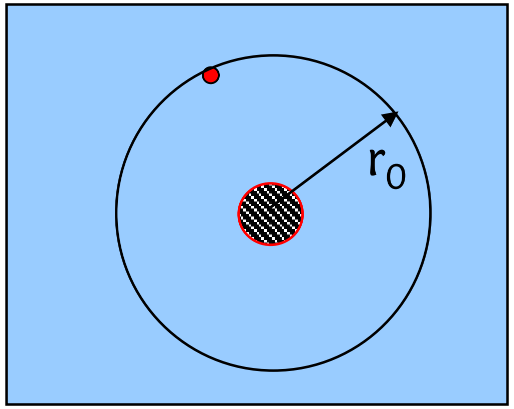
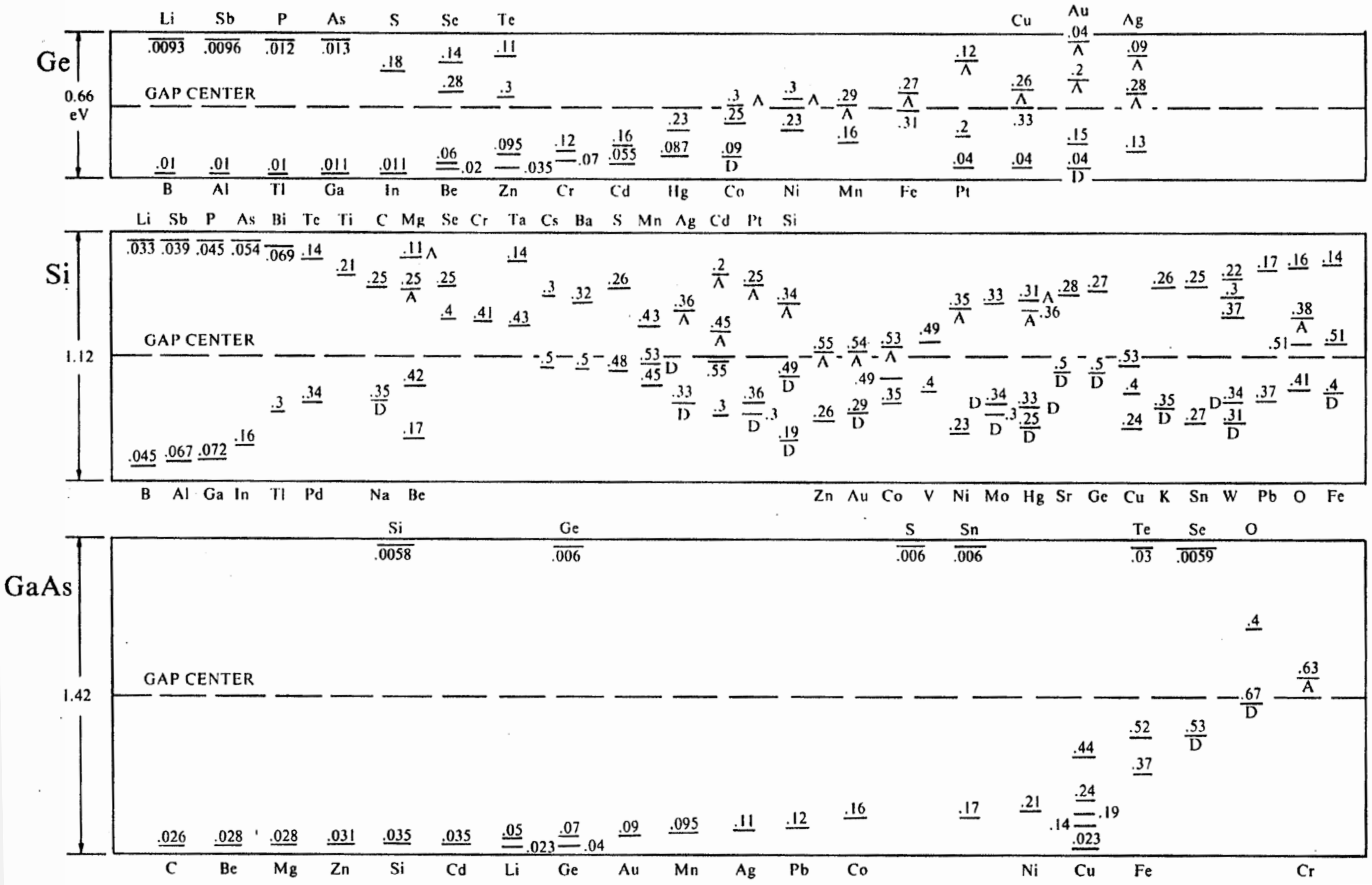
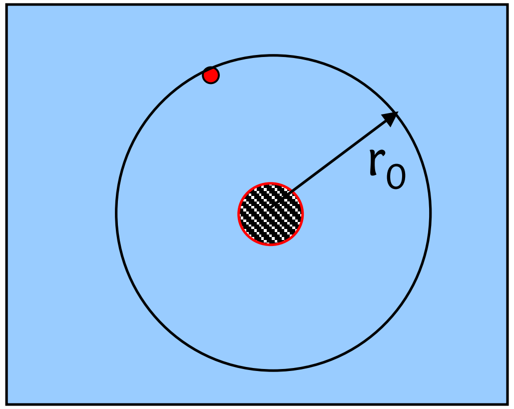


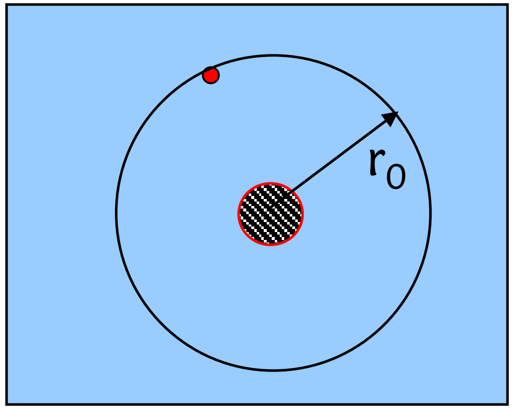
Table of Donors and Acceptors





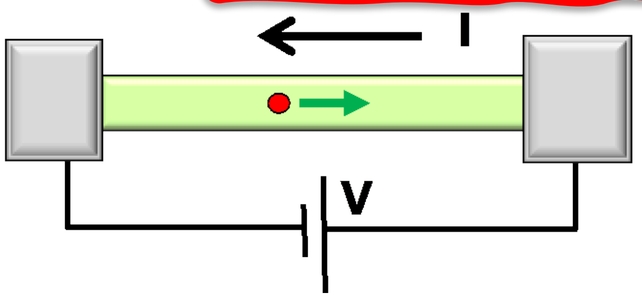
Intrinsic carrier concentration is so small that semiconductor must be doped to make it useful.

A doping atom behaves like a H-atom, except that the dielectric constant and effective masses are given by by those of the host atom.



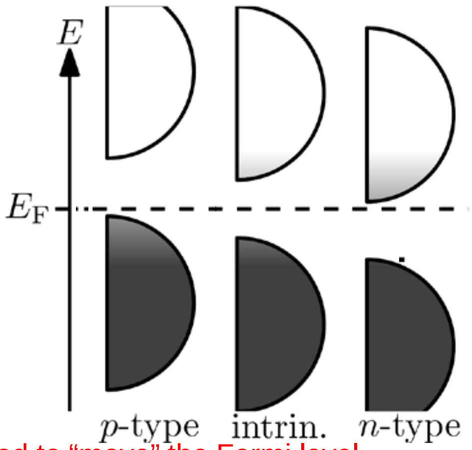
Section 14 Doping

Not Enough Electrons available



$$I = G \times V$$
$$= q \times n \times v \times A$$

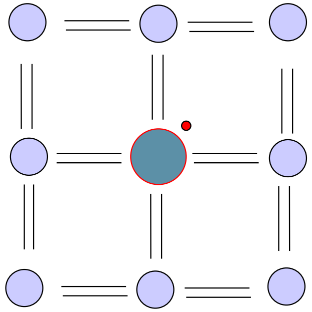
charge density velocity area

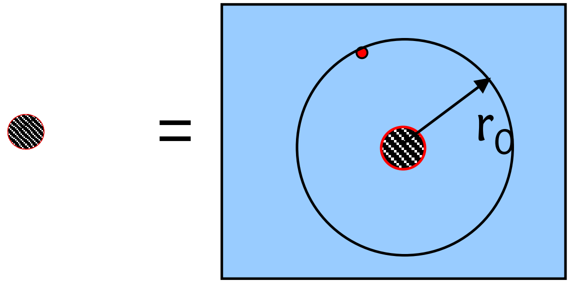


- » Need to “move” the Fermi level
- » ”add” electrons – n-type doping – E_F close to E_c
- » “add” holes – p-type doping – E_F close to E_v

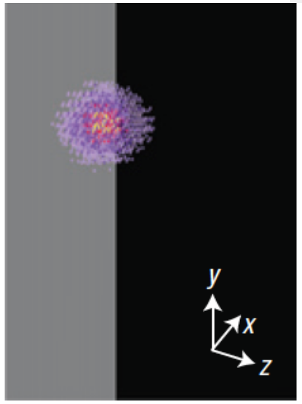
Video

- 14.1 Basic concepts of donors and acceptors





A doping atom behaves like a H-atom, except that the dielectric constant and effective masses are given by by those of the host atom.



Video

- 14.2

Video

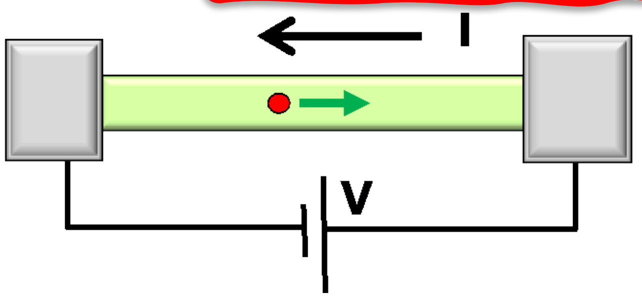
- 14.3

Video

- 14.4

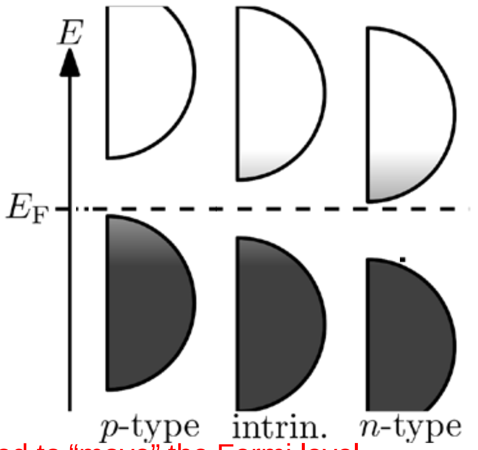
Section 14
Doping

Not Enough Electrons available



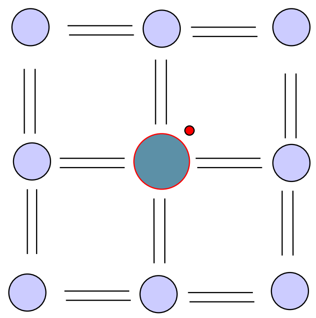
$$I = G \times V$$
$$= q \times n \times v \times A$$

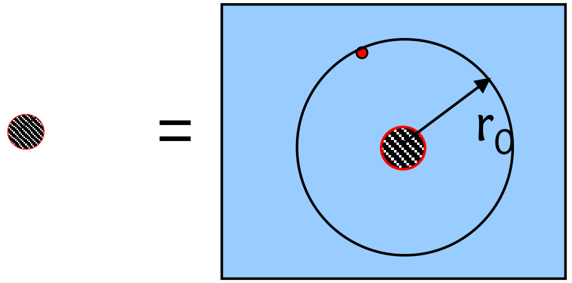
charge density velocity area



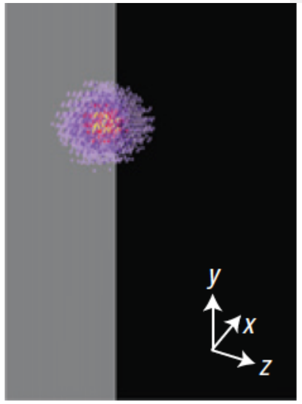
» Need to "move" the Fermi level
» "add" electrons – n-type doping – E_F close to E_c
» "add" holes – p-type doping – E_F close to E_v

- 14.1 Basic concepts of donors and acceptors





A doping atom behaves like a H-atom, except that the dielectric constant and effective masses are given by by those of the host atom.



- 14.2 Statistics of donor and acceptor levels
- 14.3

- 14.4

Video

Video

Video

Video