Condensed Matter Physics I

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Previously

Semiconductors:

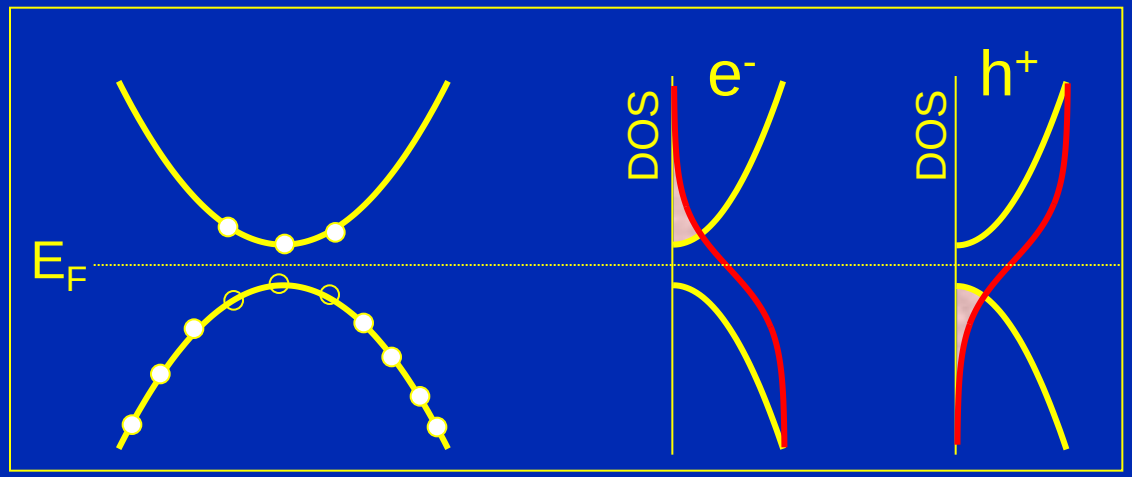
- Direct gap / Indirect gap
- Holes
- Cyclotron resonance

Today

Seminconductors

- Intrinsic / Extrinsic, carrier statistics
- Homogeneous / Inhomogeneous
- Quantum Hall effect

Carrier density



$$n = \int_{E_c}^{\infty} dE\, D_c(E) \cdot f_e(E) = n_o \cdot e^{\frac{\mu - E_c}{k_b T}} \qquad n_o = 2\left(\frac{m_c^* k_b T}{\pi \hbar^2}\right)^{3/2}$$

$$p = \int_{-\infty}^{E_v} dE\, D_v(E) \cdot f_h(E) = p_o \cdot e^{\frac{E_v - \mu}{k_b T}} \qquad p_o = 2\left(\frac{m_v^* k_b T}{\pi \hbar^2}\right)^{3/2}$$

$$n \cdot p = n_o p_o \cdot e^{-\frac{E_g}{2 k_b T}}$$

Independent of μ or doping

Intrinsic case

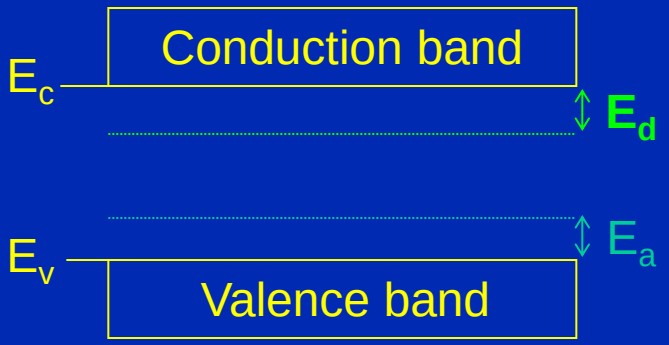
Density: $n_i \equiv p_i = \sqrt{n_o p_o} \cdot e^{-\frac{E_g}{k_b T}}$

From n = p :

$$n_o \cdot e^{\frac{\mu - E_c}{k_b T}} = p_o \cdot e^{\frac{E_v - \mu}{k_b T}}$$

$$E_F = \mu = \frac{1}{2} E_g + \frac{3}{4} k_b T \cdot \ln\left(\frac{m_h^*}{m_e^*}\right) \qquad \text{(setting } E_v = 0\text{)}$$

Extrinsic case



'H problem' with $e^2 \rightarrow e^2/\varepsilon$ & $m \rightarrow m^*$

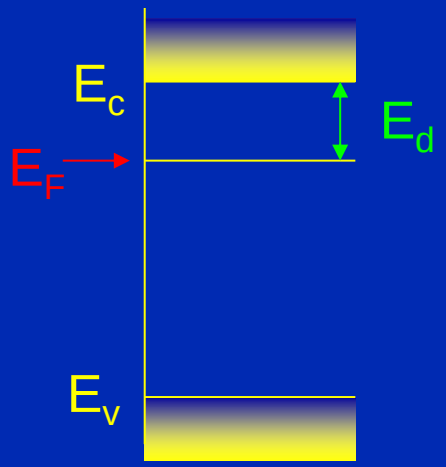
Ionization energy 1 'Ry': $E_d = \frac{m^* e^4}{2\hbar^2 \varepsilon^2} = \frac{m^*}{m_o}\frac{1}{\varepsilon^2} \cdot 13.6\ \text{eV}$

'Bohr' radius: $r_d = \frac{\hbar^2 \varepsilon}{m^* e^2} = \frac{m_o}{m^*}\varepsilon \cdot a_o$

Extrinsic

Donor and acceptor levels

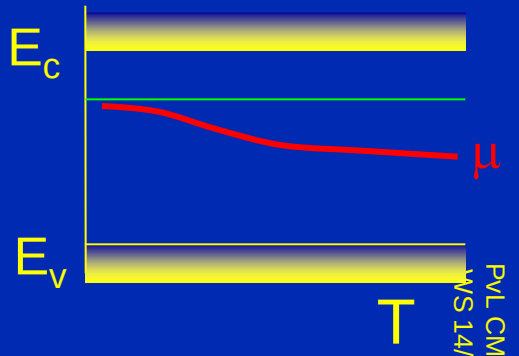
	P	As	Sb	B	Al	Ga	In
Si	45	49	39	45	57	65	157
Ge	12	13	10	10	10	11	11



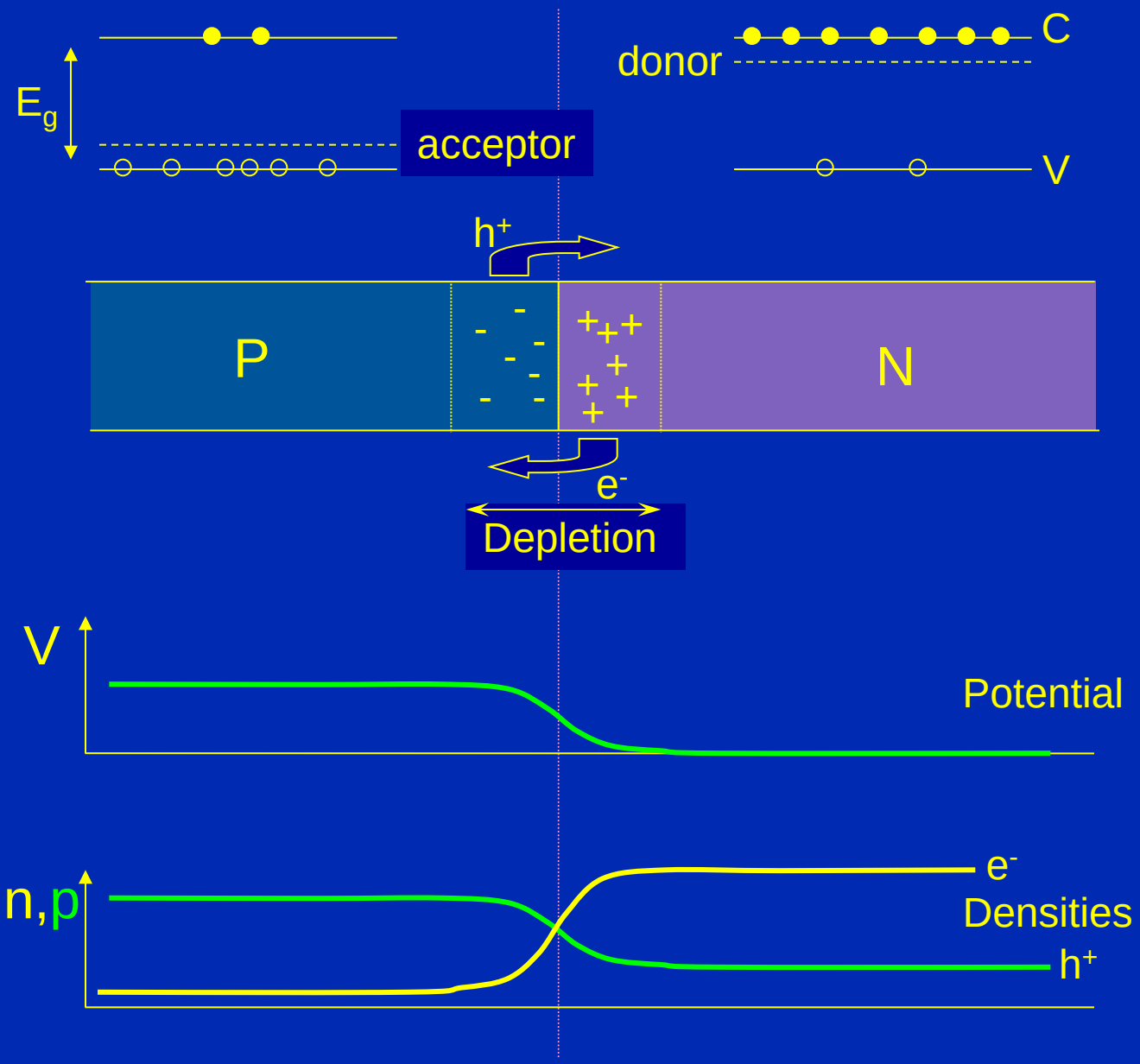
$$N_d^o = N_d \cdot \langle n \rangle = N_d \frac{e^{-(\varepsilon_d-\mu)/kT} + e^{-(\varepsilon_d-\mu)/kT}}{1 + e^{-(\varepsilon_d-\mu)/kT} + e^{-(\varepsilon_d-\mu)/kT}} = N_d \frac{1}{\frac{1}{2} e^{(\varepsilon_d-\mu)/kT} + 1}$$

$$n_d = N_d - N_d^o = N_d \left(1 - \frac{2}{e^{(\varepsilon_d-\mu)/kT} + 2} \right)$$

$$\left. \begin{array}{l} n_c = p_i + n_d \\ p_i \approx n_i \end{array} \right\} \rightarrow n \approx \sqrt{N_d n_0} \cdot e^{-E_d/2k_bT}$$



P-N Junction


C
donor
E_g
acceptor
V
h^+
P
N
e^-
Depletion
V
Potential
n,p
e^-
Densities
h^+

Drift (thermally exc.)
e^- ⟶

Diffusion (E-field)
⟵ e^-

No bias

E_c

E_v

$j_{drift} \equiv j_{diffusion}$

Forward bias

V

E_c

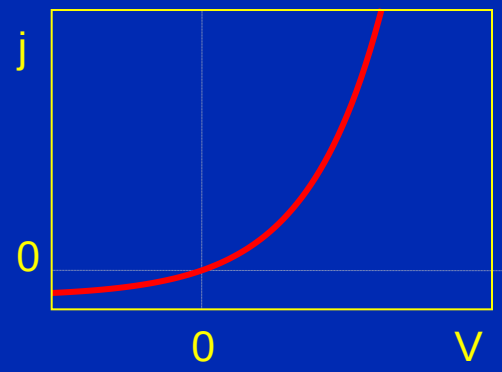
$j_{diffusion} > j_{drift}$

Reverse bias

V

E_c

$j_{diffusion} < j_{drift}$



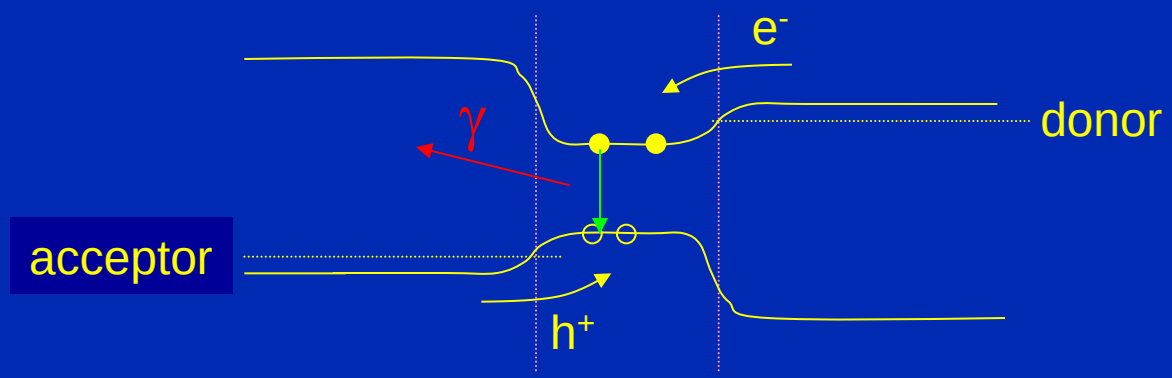
Other heterogeneous S.C.

Recombination: $e^- + h^+ \rightarrow \gamma$

LED and Semiconductor laser

$GaAs_{1-x}P_x$

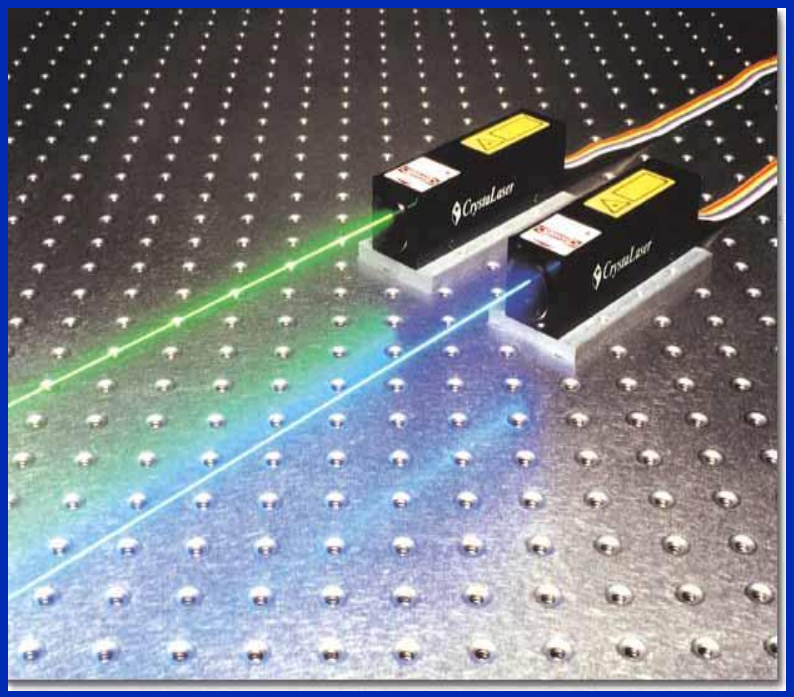
$In_xGa_{1-x}N/Al_yGa_{1-y}N$



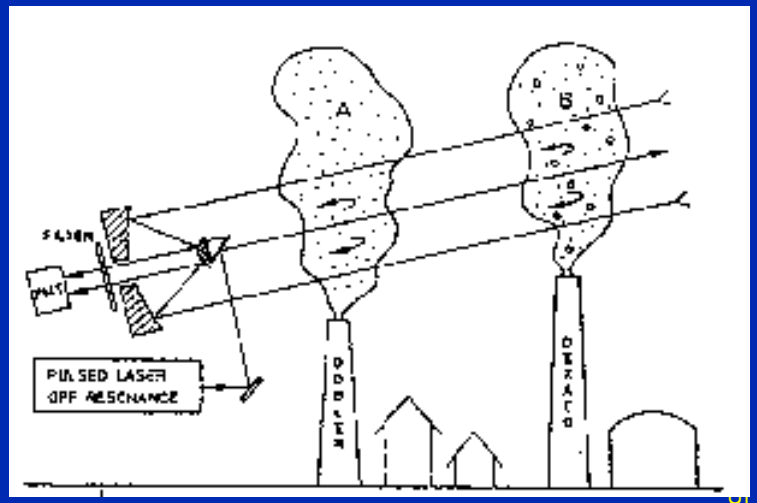
p-type

n-type

SC lasers



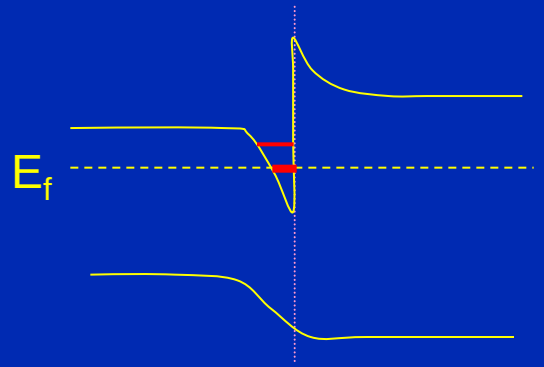
- Storage CD/DVD, MO
- Eye, artery, dental Surgery
- Diagnostic (Caries, Cancer)
- Environmental monitoring
- Remote sensing (speed, chemicals)
- Motion control
- Star Wars, guns
- … …
- …



Heterostructure

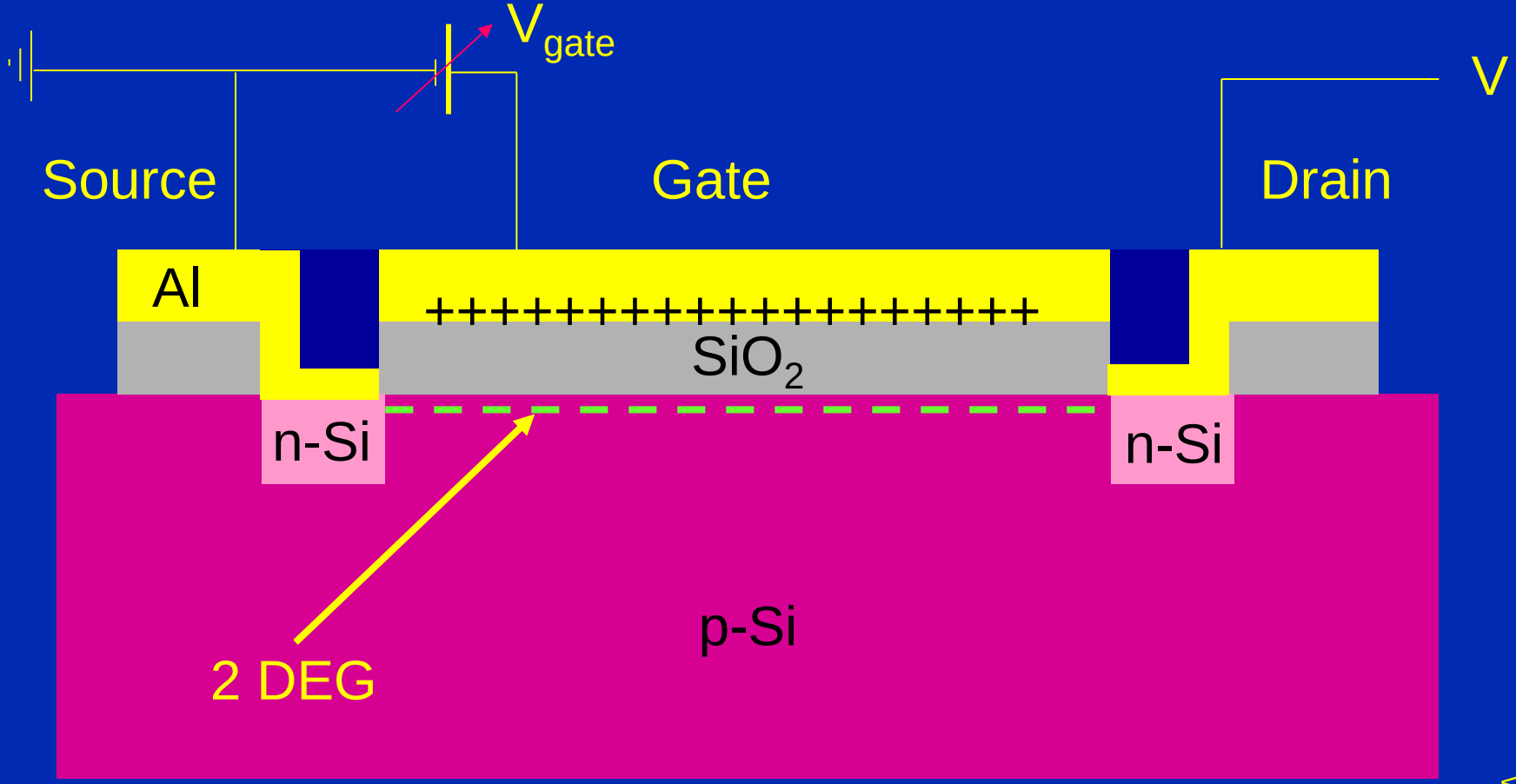
Heterostructure: Lateral confinement => 2 DEG

GaAs

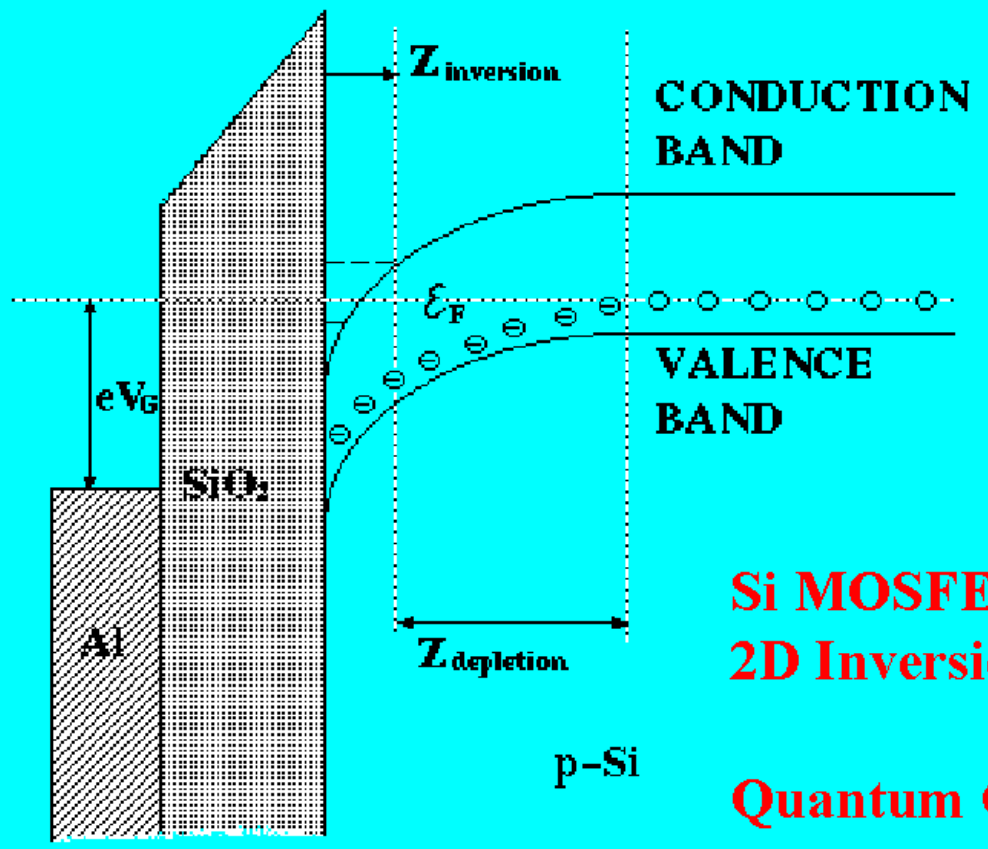


$Al_xGa_{1-x}As$ (n-type)

MOSFET 2DEG

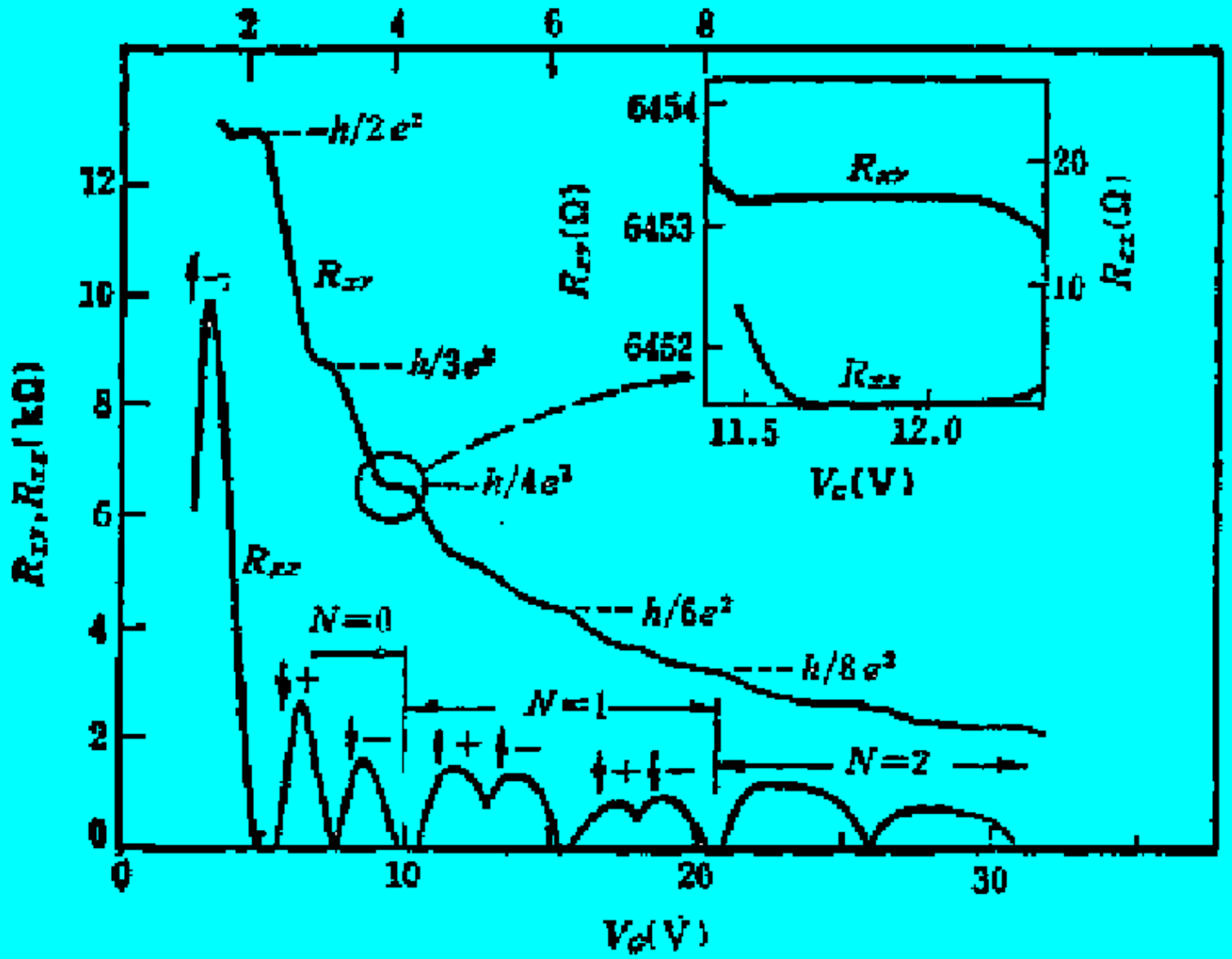


Band diagram MOSFET



Si MOSFET with 2D Inversion Layer

Quantum Confinement

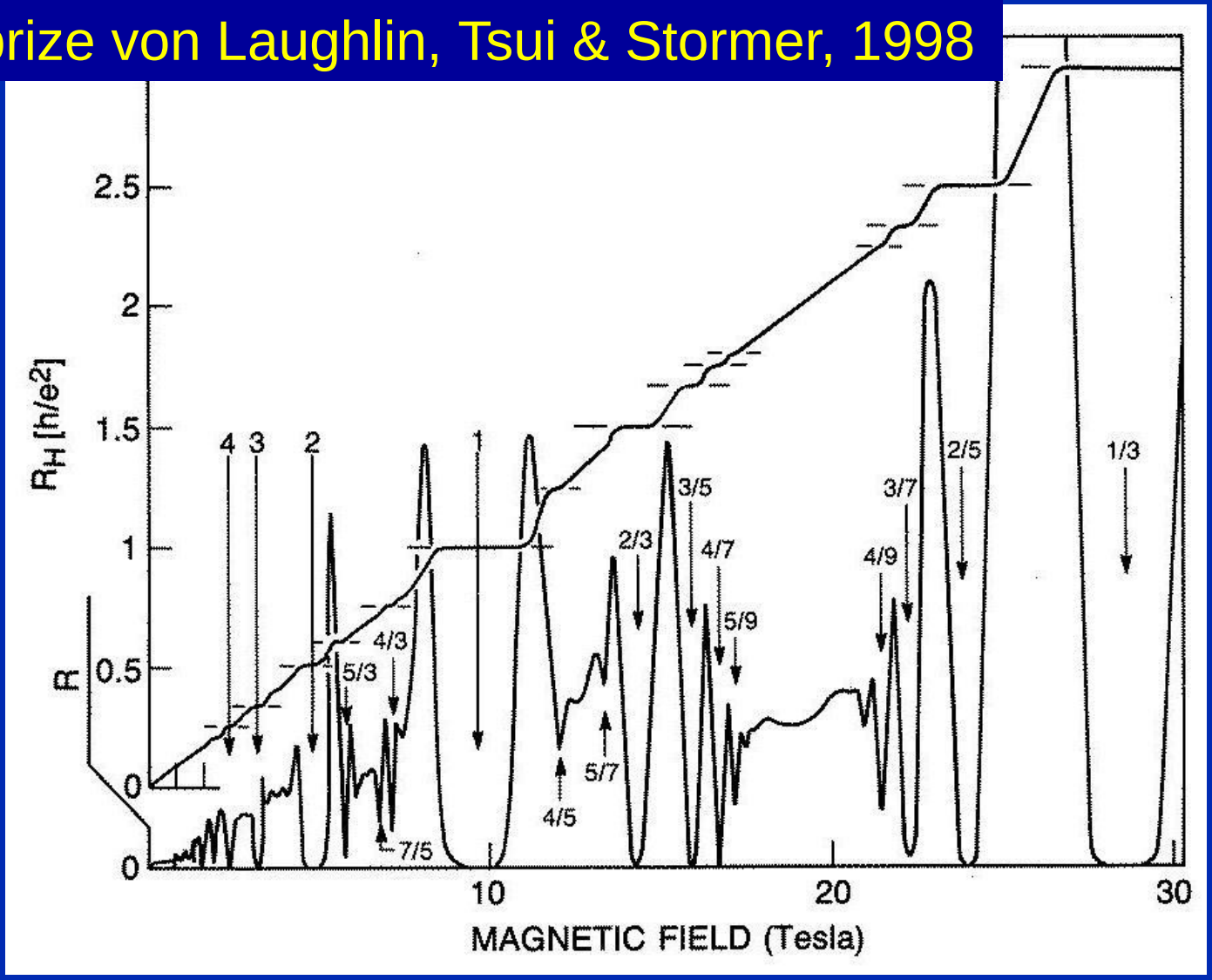


Integer Quantum Hall effect on Si-MOSFET

Nobel prize von Klitzing, 1985

Fractional quantum hall effect

Nobel prize von Laughlin, Tsui & Stormer, 1998



Composite fermions