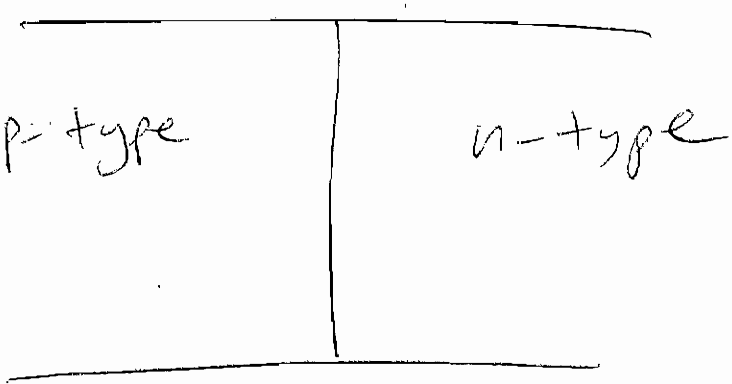
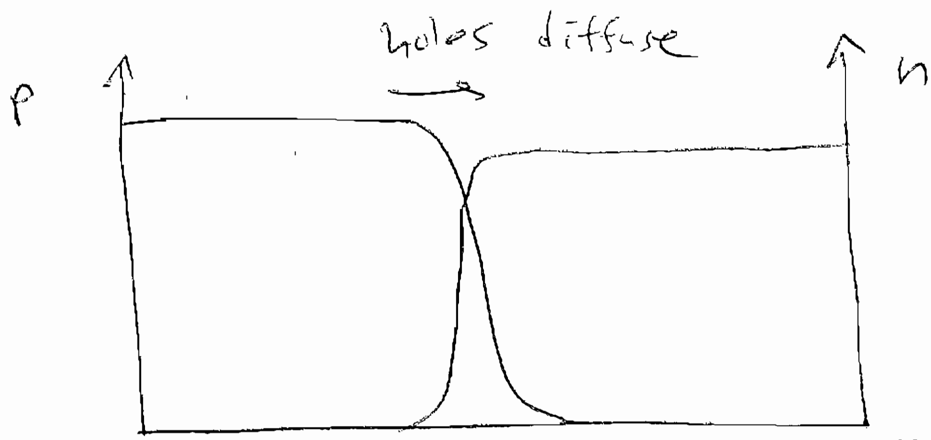
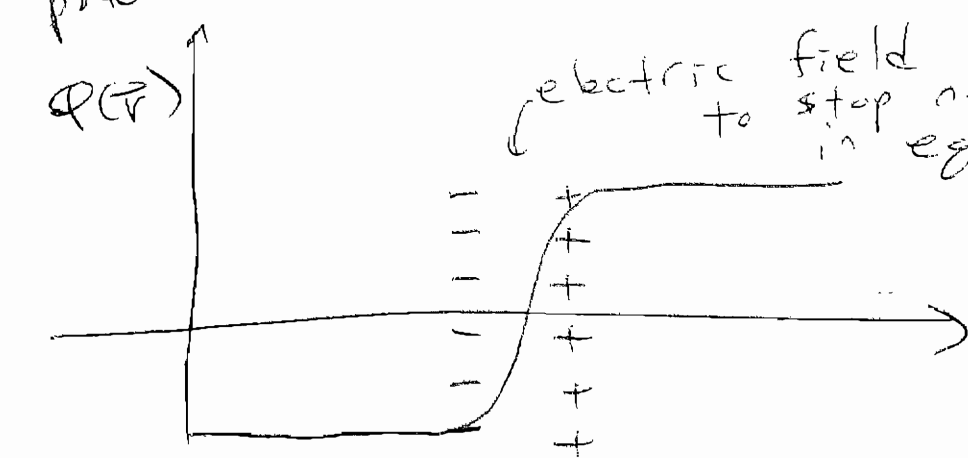
Semiconductor devices

pn - Junction



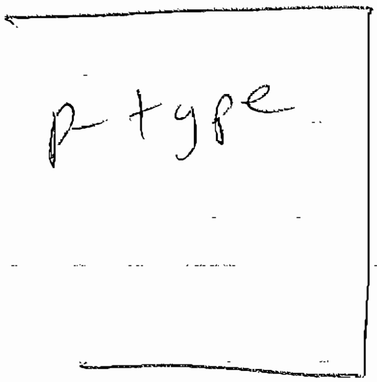


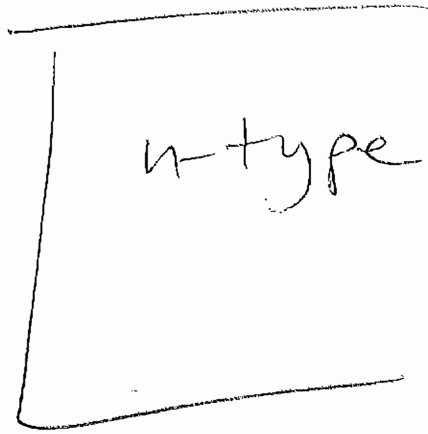
← electrons diffuse across junction



electric field builds up to stop net current in equilibrium

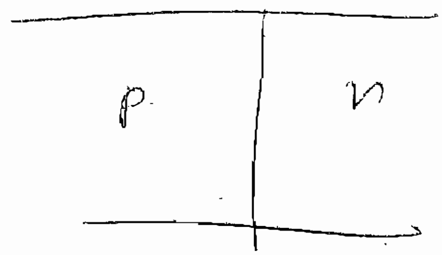
As $T \to 0$





$\mu_L \simeq \varepsilon_v + \frac{E_g}{2}$ $\qquad$ $\mu_R \cong \varepsilon_c - \frac{E_d}{2}$

In contact:



$$\mu_L = \varepsilon_v + \frac{E_g}{2} - eV_L$$

$$= \mu_R = \varepsilon_c - \frac{E_d}{2} - eV_R$$

(draw picture)

$$e\Delta V = e(V_R - V_L) \cong \varepsilon_c - \varepsilon_v + \frac{E_g - E_d}{2}$$

$$\approx \varepsilon_c - \varepsilon_v$$

voltage drop across p-n junction

For $\mathcal{E}_c - \mu$, $\mu - \mathcal{E}_v \gg k_B T$, both electrons and holes form ideal gases. In equilibrium, the chemical potential of each carrier is constant across the junction:

$$\mu_e = -e\varphi(\vec{r}) + k_B T \ln\left(n(\vec{r}) / n_{Qe} \right)$$

$$\mu_h = +e\varphi(\vec{r}) + k_B T \ln\left(p(\vec{r}) / n_{Qh} \right)$$

$$n_{Qe} = 2\left(\frac{m_e k_B T}{2\pi\hbar^2} \right)^{3/2}$$

$$n_{Qh} = 2\left(\frac{m_h k_B T}{2\pi\hbar^2} \right)^{3/2}$$

$$k_B T \ln p(\vec{r}) + e\varphi(\vec{r}) = \text{const}$$

$$k_B T \ln n(\vec{r}) - e\varphi(\vec{r}) = \text{const}.$$

⇒ next page

The net particle flow of each carrier type is zero in equilibrium. There are two processes, which exactly cancel:

i) J_{nr} Electrons diffuse from the n-region to the p-region where they recombine with holes

(ii) J_{ng} Electrons are thermally excited in the p-region and are accelerated by the electric field of the junction into the n-region.

Analogous processes occur for holes.

Rectification

In equilibrium,

$$J_{nr}(0) + J_{ng}(0) = 0$$

Under reverse bias, a negative voltage is applied to the p-region, and positive to the n-region. The recombination current is then suppressed by the Boltzmann factor

$$J_{nr}(V) = J_{nr}(0)\, e^{-e|V|/k_B T}.$$

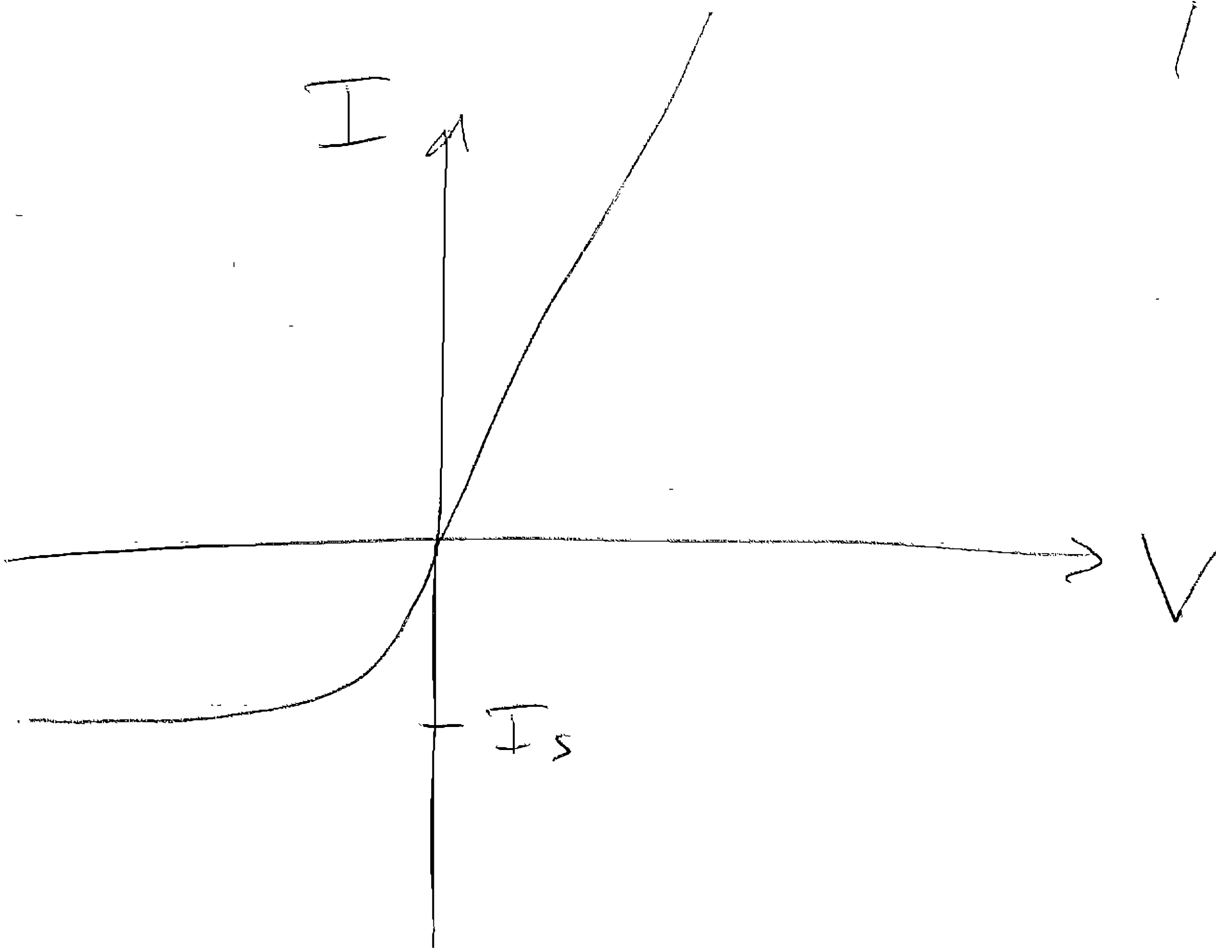
The current generated by thermally excited electrons flowing from $p \to n$ is essentially unaffected since they are flowing downhill anyway

$$J_{ng}(V) = J_{ng}(0)$$

In general:

$$I = \left[e^{eV/k_B T} - 1 \right] I_s$$

where $I_s = J_{ng}(0)$.

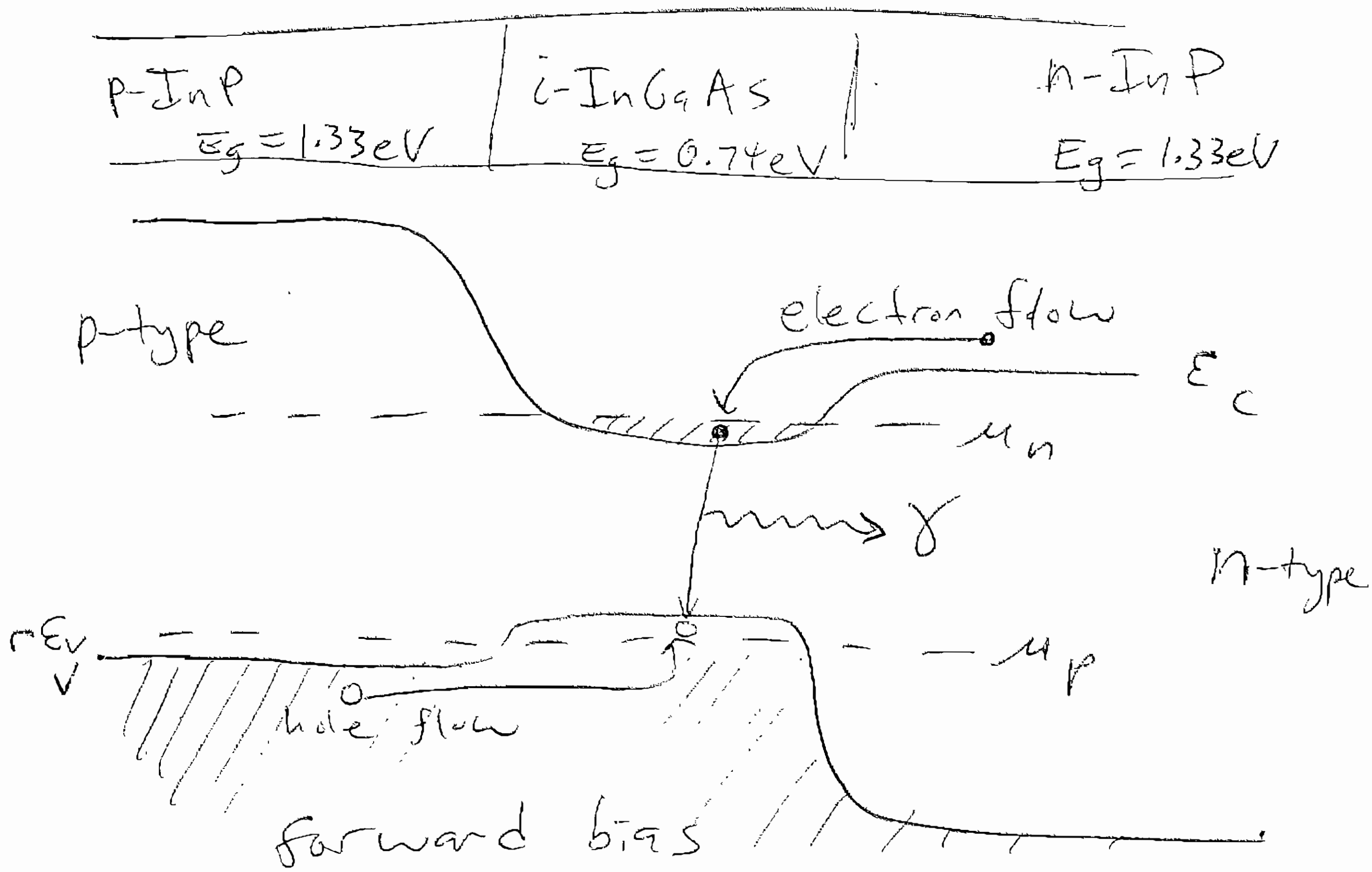


Solar cells

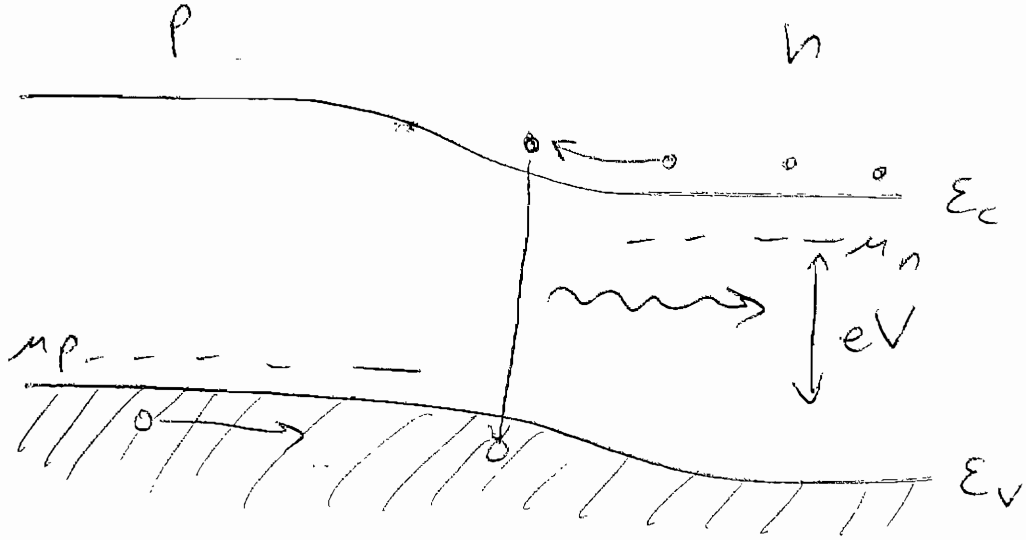
If we shine light on a p-n junction, we excite electrons on the p-side and holes on the n-side, which diffuse to the junction and are accelerated across by the junction electric field. The work done by the junction electric field can be used in an external circuit.

$\Rightarrow$ LED

semiconductor lasers



Light-emitting diodes



Under forward ~~reverse~~ bias, the recombination current is enhanced, generating photons.

$\Rightarrow$ Laser

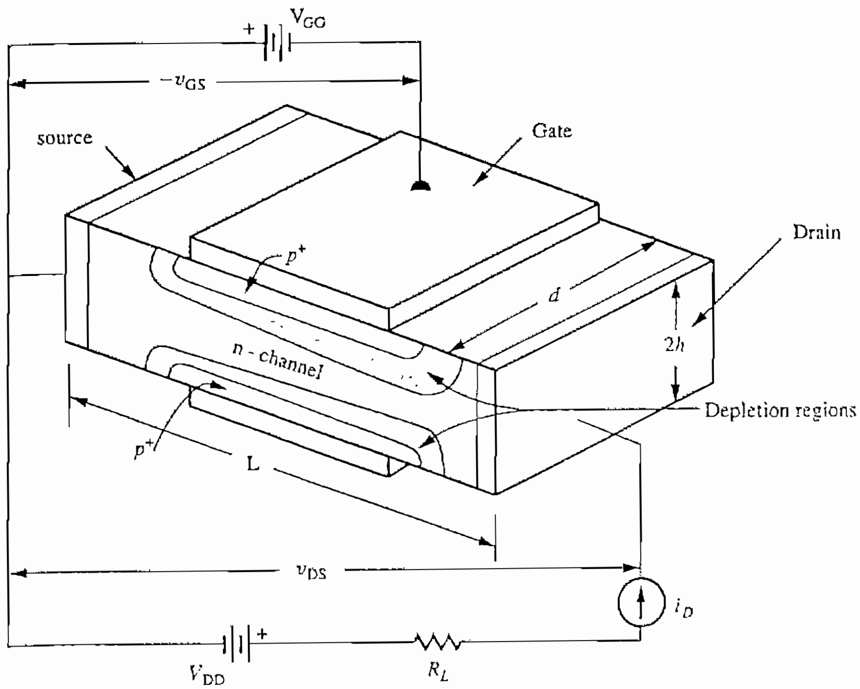


FIGURE 10.2
Essential components of a junction field-effect transistor (JFET).

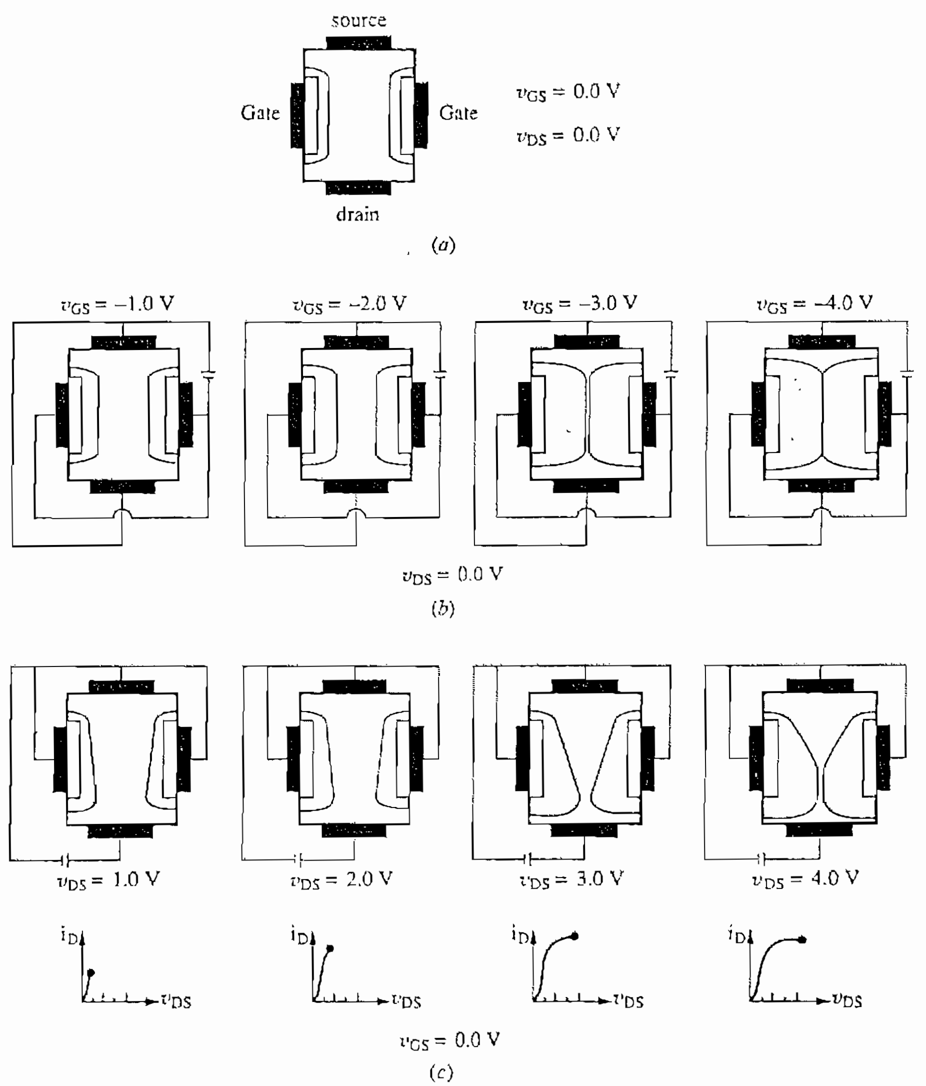


FIGURE 10.3
Operational characteristics of a JFET with V_P = −3.0 V. (*a*) With no bias. Depletion layers are the usual diode depletion layers. (*b*) Channel height for various gate-source voltages with v_{DS} = 0. Beyond v_{GS} = −3.0 V, the channel is closed, the transistor at cutoff. (*c*) Current increases with increasing v_{DS} for no gate bias.

2D Electron Gas

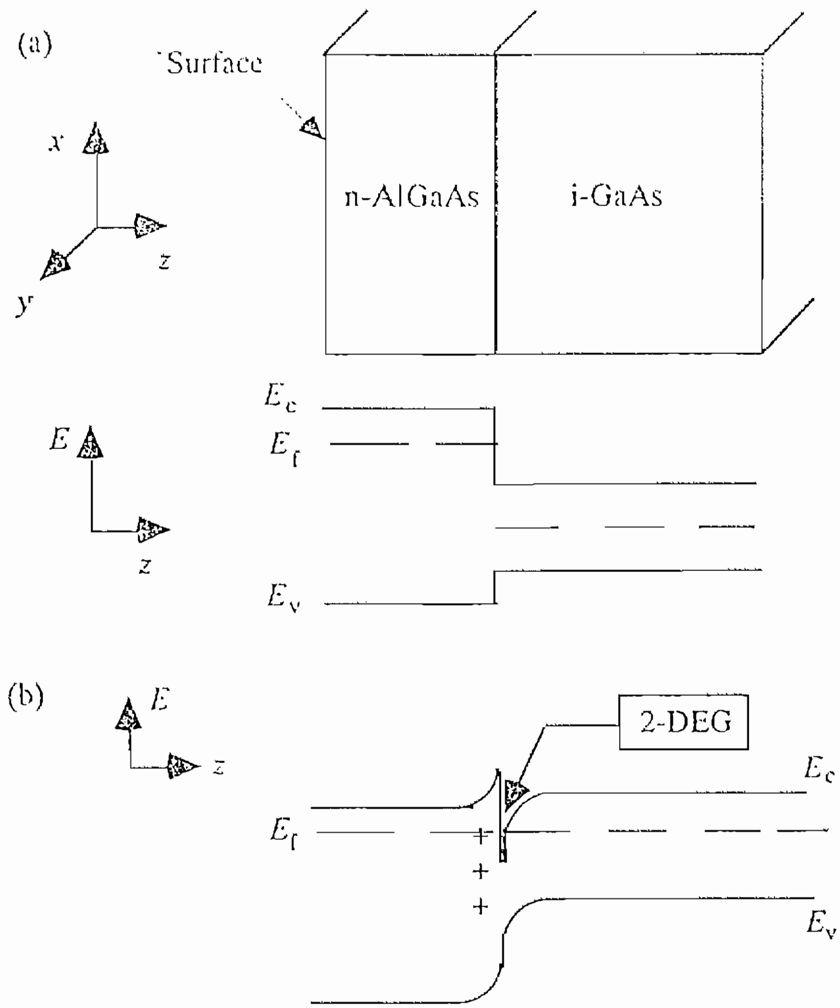


Fig. 1.1.1. Conduction and valence band line-up at a junction between an n-type AlGaAs and intrinsic GaAs, (*a*) before and (*b*) after charge transfer has taken place. Note that this is a cross-sectional view. Patterning (as shown in Fig. 0.3) is done on the surface (*x*–*y* plane) using lithographic techniques.

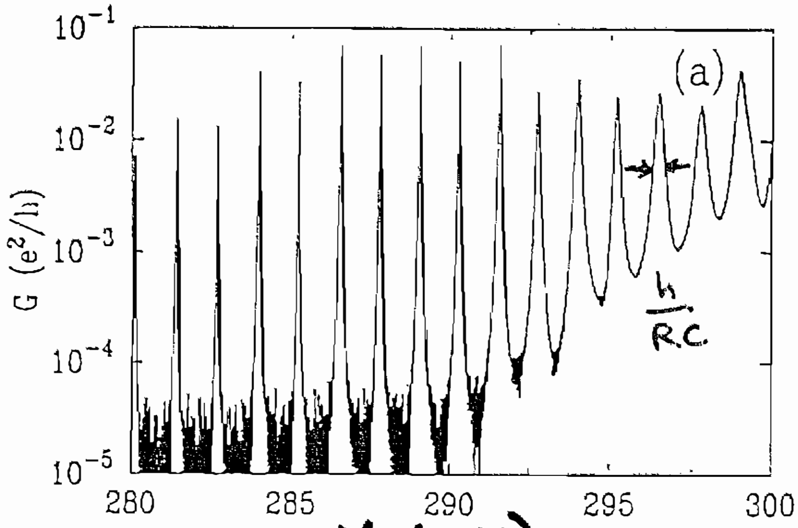
Coulomb Blockade

$$F(N) \simeq \frac{(Ne)^2}{2C} \qquad \mu(N) = \frac{\partial F}{\partial N} \simeq N\frac{e^2}{C}$$

occurs when

$kT \ll \frac{e^2}{C}$

$G < \frac{e^2}{h}$



Hubbard type interaction

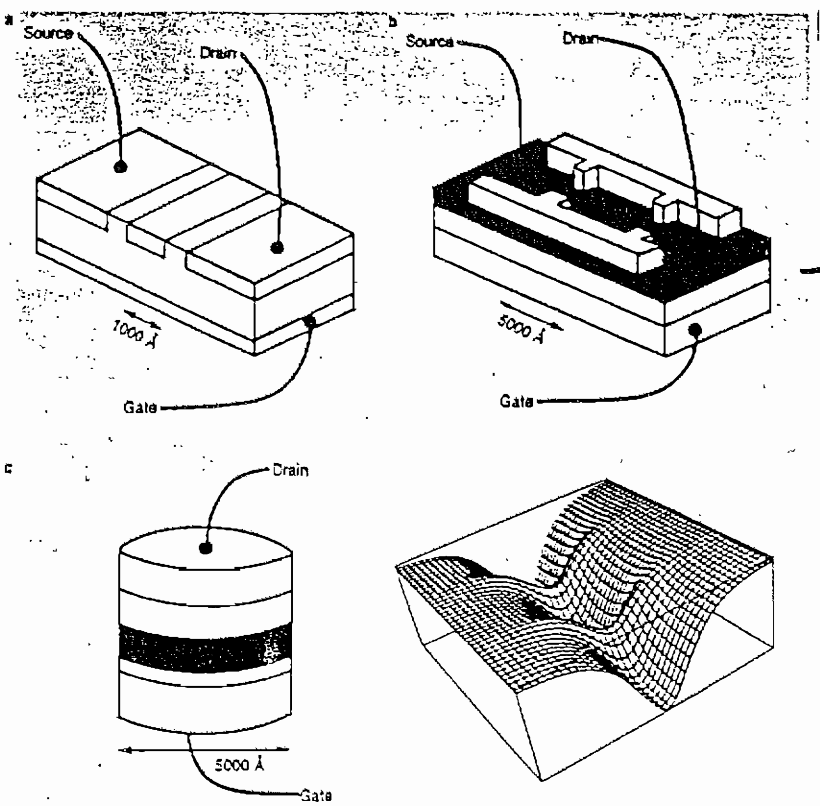
$U = \frac{e^2}{C}$

Quantum Dots

"artificial atoms"

$r \gg a_B$

$$\frac{e^2}{\varepsilon r} \gg \frac{\hbar^2}{m^* r^2}$$



Courtesy of M. Kastner

Coulomb Blockade

$$kT \ll \frac{e^2}{C}$$

and

$$\frac{h}{RC} < \frac{e^2}{C}$$

$$\Rightarrow \frac{h}{e^2} < R$$

$\Rightarrow$ Single-electron transistor