ECE606: Solid State Devices

Lecture 30: Heterojunction Bipolar Transistor (I)

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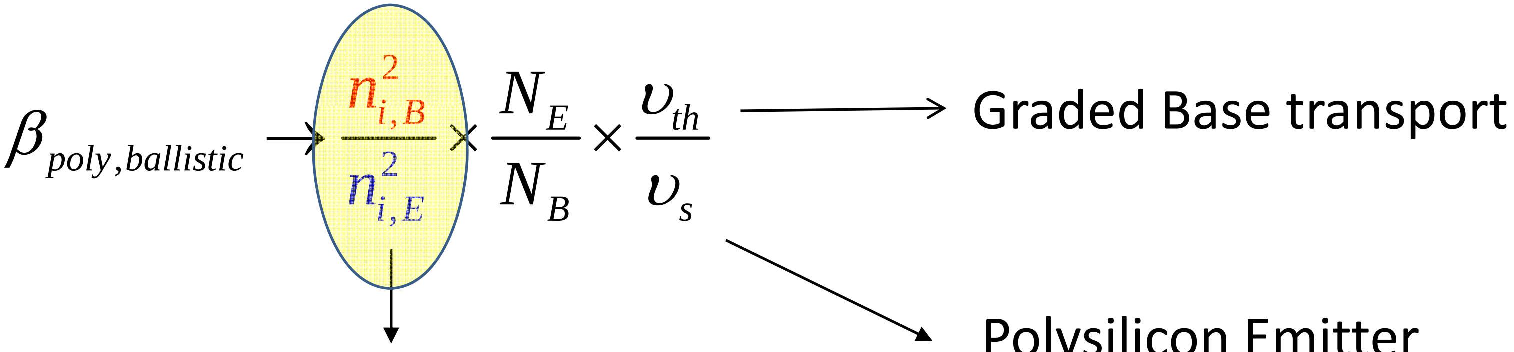
Outline

1. **Introduction**
2. Equilibrium solution for heterojunction
3. Types of heterojunctions
4. Conclusions

"Heterostructure Fundamentals," by Mark Lundstrom, Purdue University, 1995.

Herbert Kroemer, "Heterostructure bipolar transistors and integrated circuits," Proc. *IEEE* , **70**, pp. 13-25, 1982.

How to make a better Transistor



$$\beta_{poly,ballistic} \rightarrow \frac{n_{i,B}^{2}}{n_{i,E}^{2}} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

Graded Base transport

Polysilicon Emitter

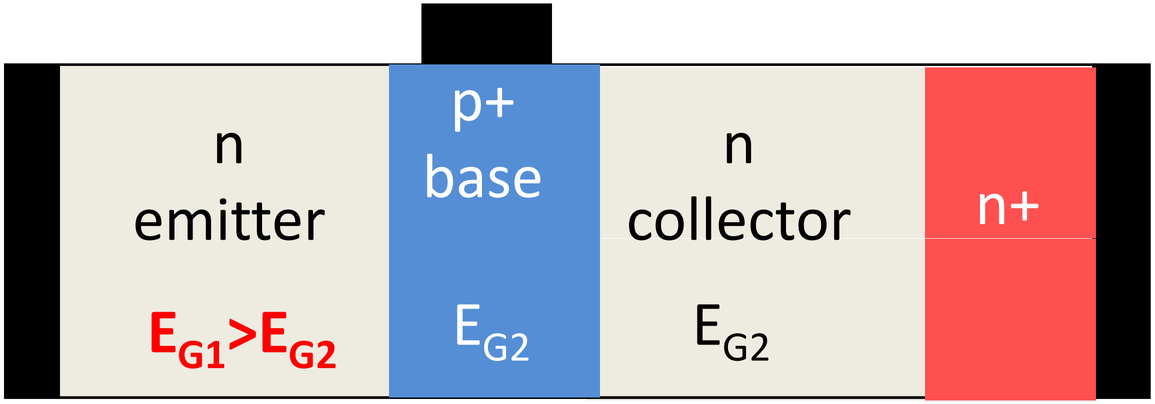
Heterojunction bipolar transistor

$$\frac{n_{i,B}^{2}}{n_{i,E}^{2}} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E}-E_{g,B}\right)\beta}$$

Emitter bandgap > Base Bandgap

Heterojunction Bipolar Transistors

i) Wide gap Emitter HBT



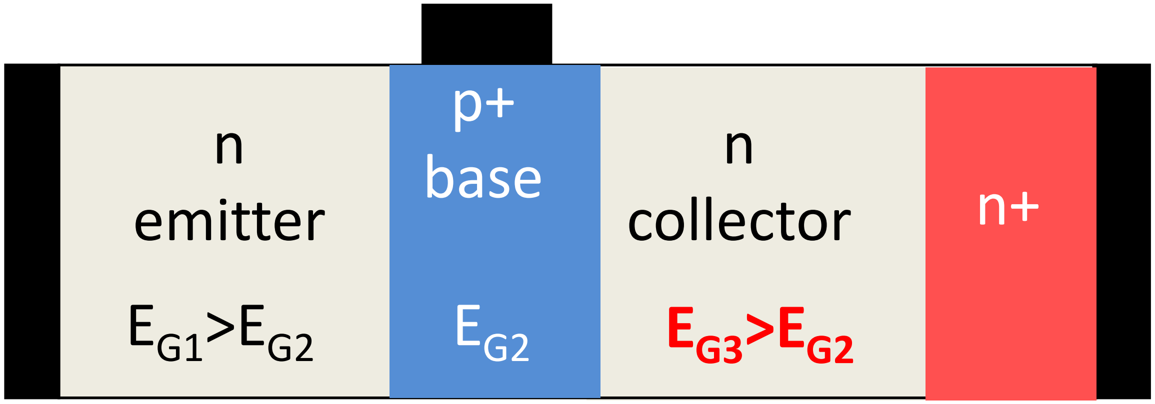
n
emitter
$E_{G1}>E_{G2}$

p+
base
E_{G2}

n
collector
E_{G2}

n+

ii) **Double** Heterojunction Bipolar Transistor



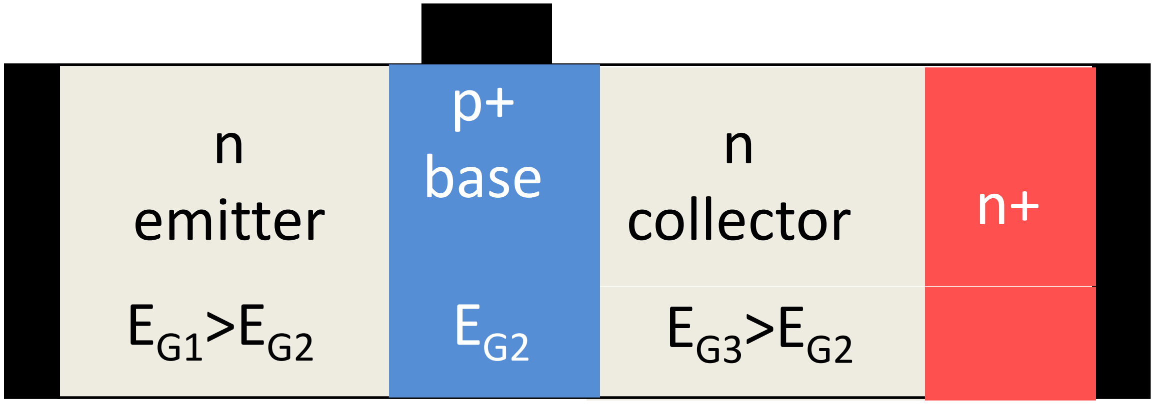
n
emitter
$E_{G1}>E_{G2}$

p+
base
E_{G2}

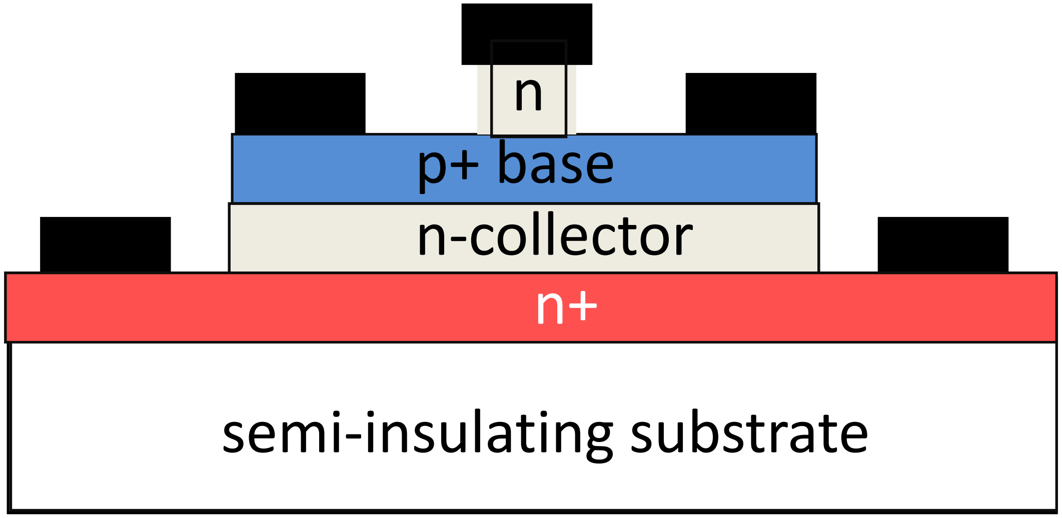
n
collector
$E_{G3}>E_{G2}$

n+

Mesa HBTs



Mesa HBT



Applications

1) **Optical fiber communications**

   -40Gb/s…….160Gb/s

2) **Wideband, high-resolution DA/AD converters and digital frequency synthesizers**

   -military radar and communications

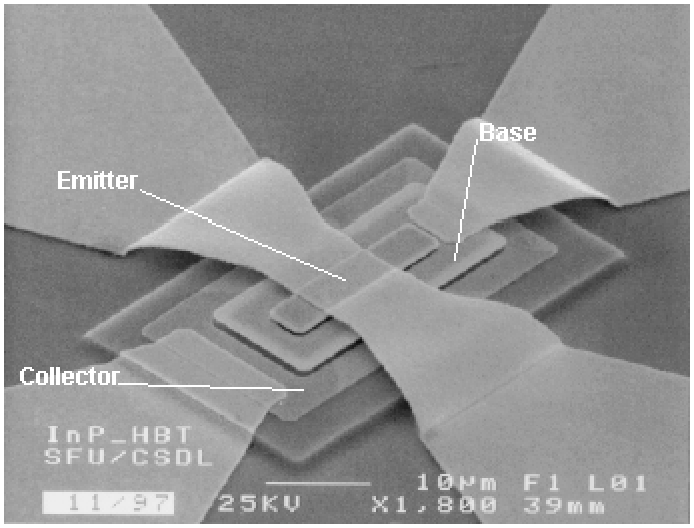
3) **Monolithic, millimeter-wave IC's (MMIC's)**

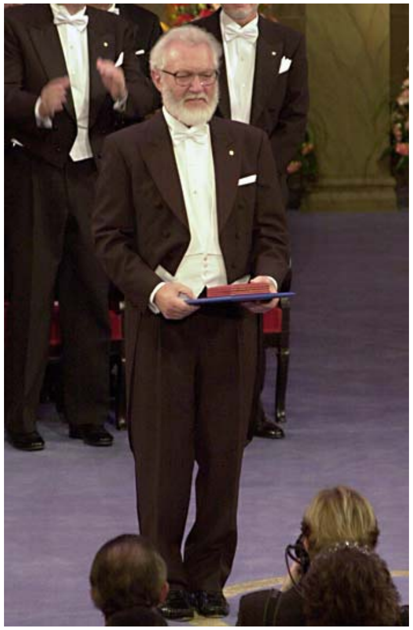
   -front ends for receivers and transmitters

future need for transistors with 1 THz power-gain cutoff freq.

Background

A heterojunction bipolar transistor





Kroemer

Schokley realized that HBT is possible, but Kroemer really provided the foundation of the field and worked out the details.

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Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT	◆				
MOS					

Bandgaps and Lattice Matching

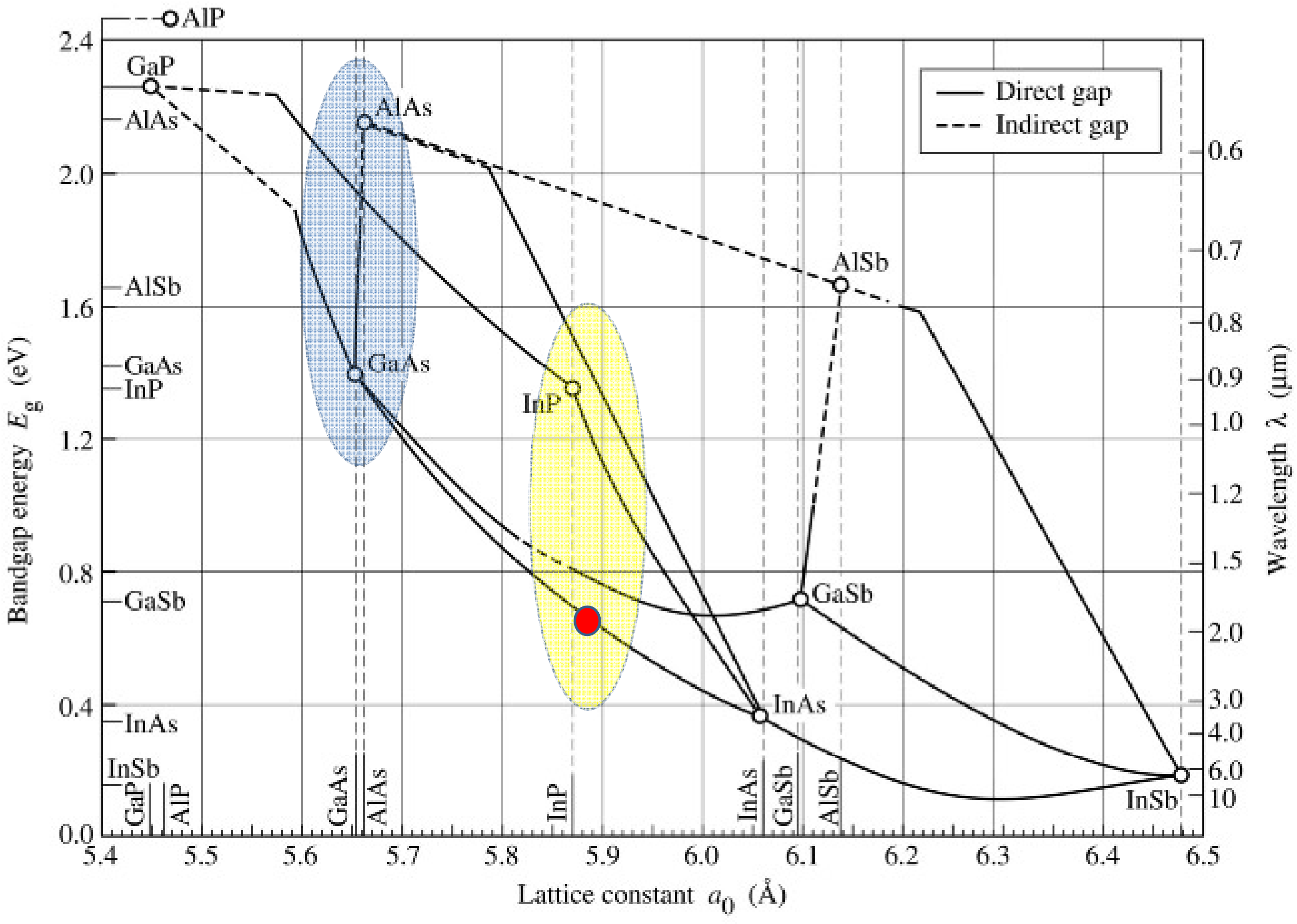


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

Band Diagram at Equilibrium

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

Equilibrium

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

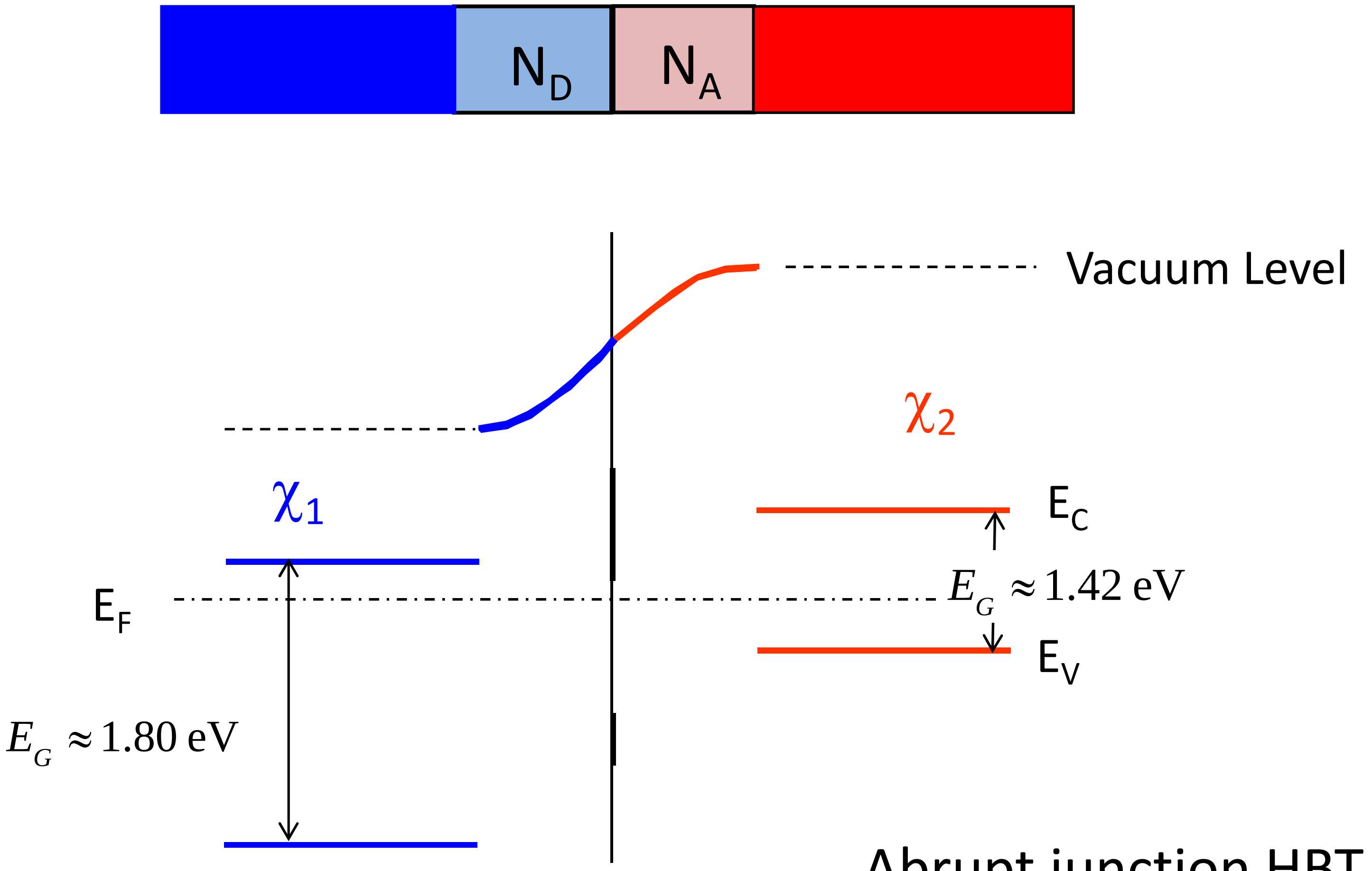
$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

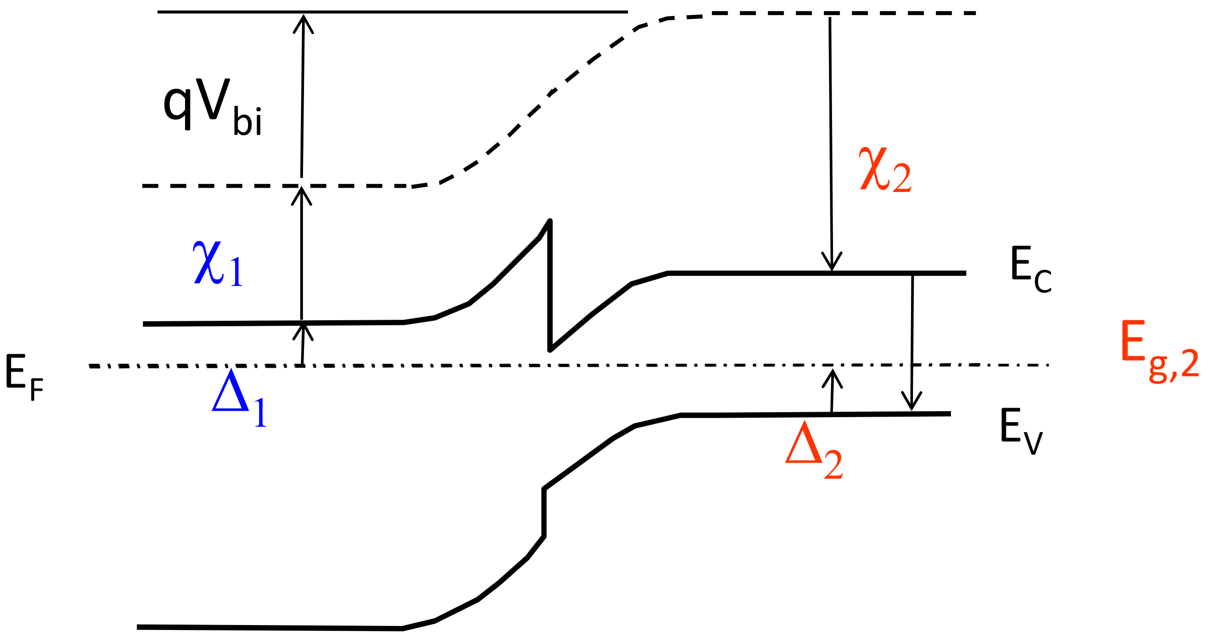
N-Al$_{0.3}$Ga$_{0.7}$As: p-GaAs (Type-I Heterojunction)



Abrupt junction HBT

Built-in Potential: Boundary Condition @Infinity

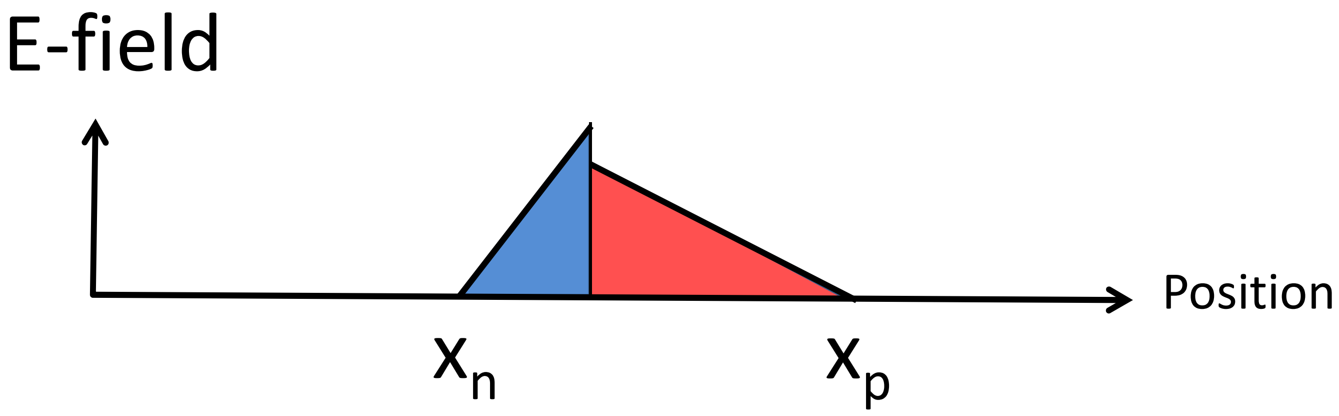
$$\Delta_1 + \chi_1 + qV_{bi} = E_{g,2} - \Delta_2 + \chi_2$$



$$qV_{bi} = E_{g,2} - \Delta_2 - \Delta_1 + \chi_2 - \chi_1$$

$$= k_B T \, ln \frac{N_A N_D}{N_{V,2} N_{C,1} e^{-E_{g,2}/k_B T}} + (\chi_2 - \chi_1)$$

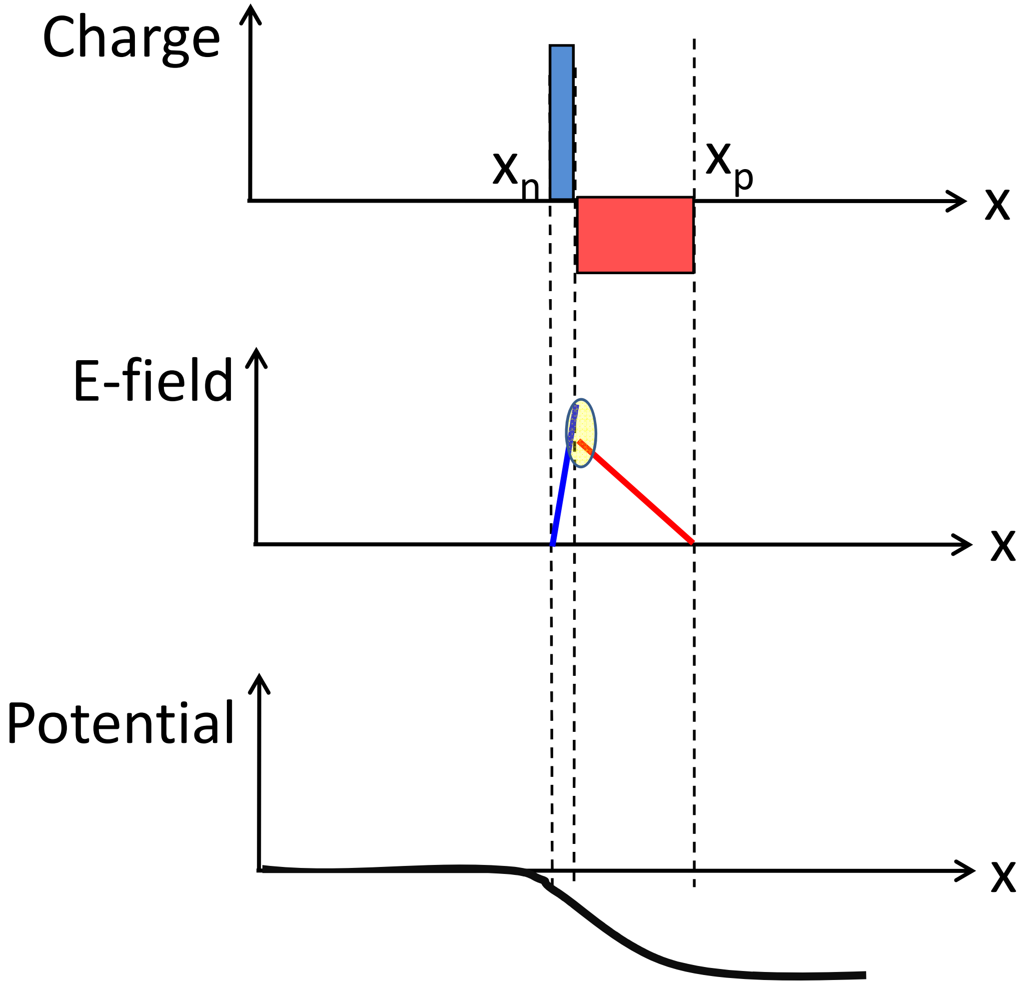
Interface Boundary Conditions



$$\kappa_1 \varepsilon_0 E\left(0^-\right) = \kappa_2 \varepsilon_0 E\left(0^+\right)$$

$$\kappa_1 \varepsilon_0 \left.\frac{dV}{dx}\right|_{0^-} = \kappa_2 \varepsilon_0 \left.\frac{dV}{dx}\right|_{0^+}$$

Analytical Solution for Heterojunctions



$$E\left(0^-\right)=\frac{qN_D x_n}{k_{s,E}\varepsilon_0}$$

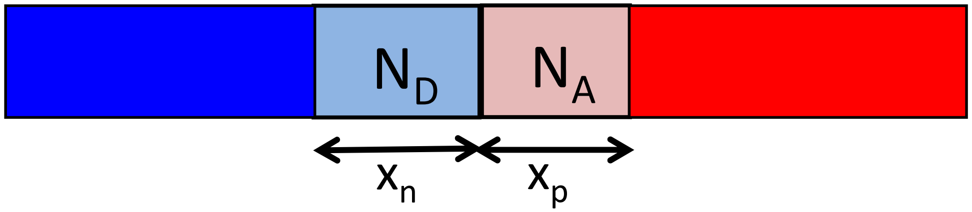
$$E\left(0^+\right)=\frac{qN_A x_p}{k_{s,B}\varepsilon_0}$$

$$\Rightarrow N_D x_n = N_A x_p$$

$$V_{bi}=\frac{E\left(0^-\right)x_n}{2}+\frac{E\left(0^+\right)x_p}{2}$$

$$=\frac{qN_D {x_n}^2}{2k_{s,E}\varepsilon_0}+\frac{qN_A {x_p}^2}{2k_{s,B}\varepsilon_0}$$

Base Emitter Depletion Region



$$N_E x_{n,BE} = N_B x_{p,BE}$$

$$V_{bi} = \frac{qN_E x_{n,BE}{}^2}{2\kappa_{s,E}\varepsilon_0} + \frac{qN_B x_{p,BE}{}^2}{2\kappa_{s,B}\varepsilon_0}$$

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$$

$$x_n = \sqrt{\frac{2\varepsilon_0}{q} \frac{\kappa_{s,E}\kappa_{s,B}N_B}{N_E\left(\kappa_{s,E}N_B + \kappa_{s,B}N_E\right)} V_{bi}}$$

$$x_p = \sqrt{\frac{2\varepsilon_0}{q} \frac{\kappa_{s,E}\kappa_{s,B}N_E}{N_B\left(\kappa_{s,E}N_B + \kappa_{s,B}N_E\right)} V_{bi}}$$

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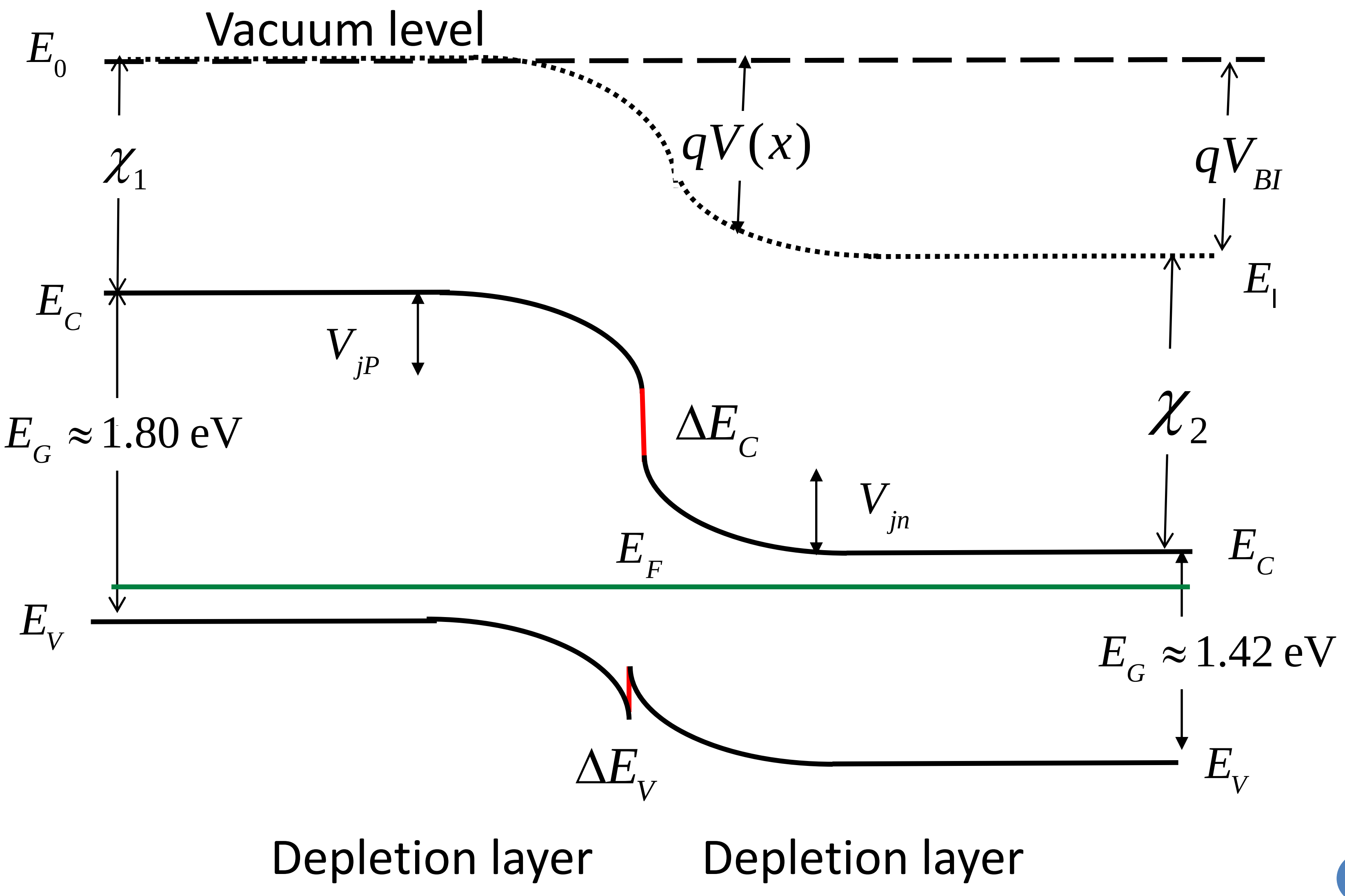
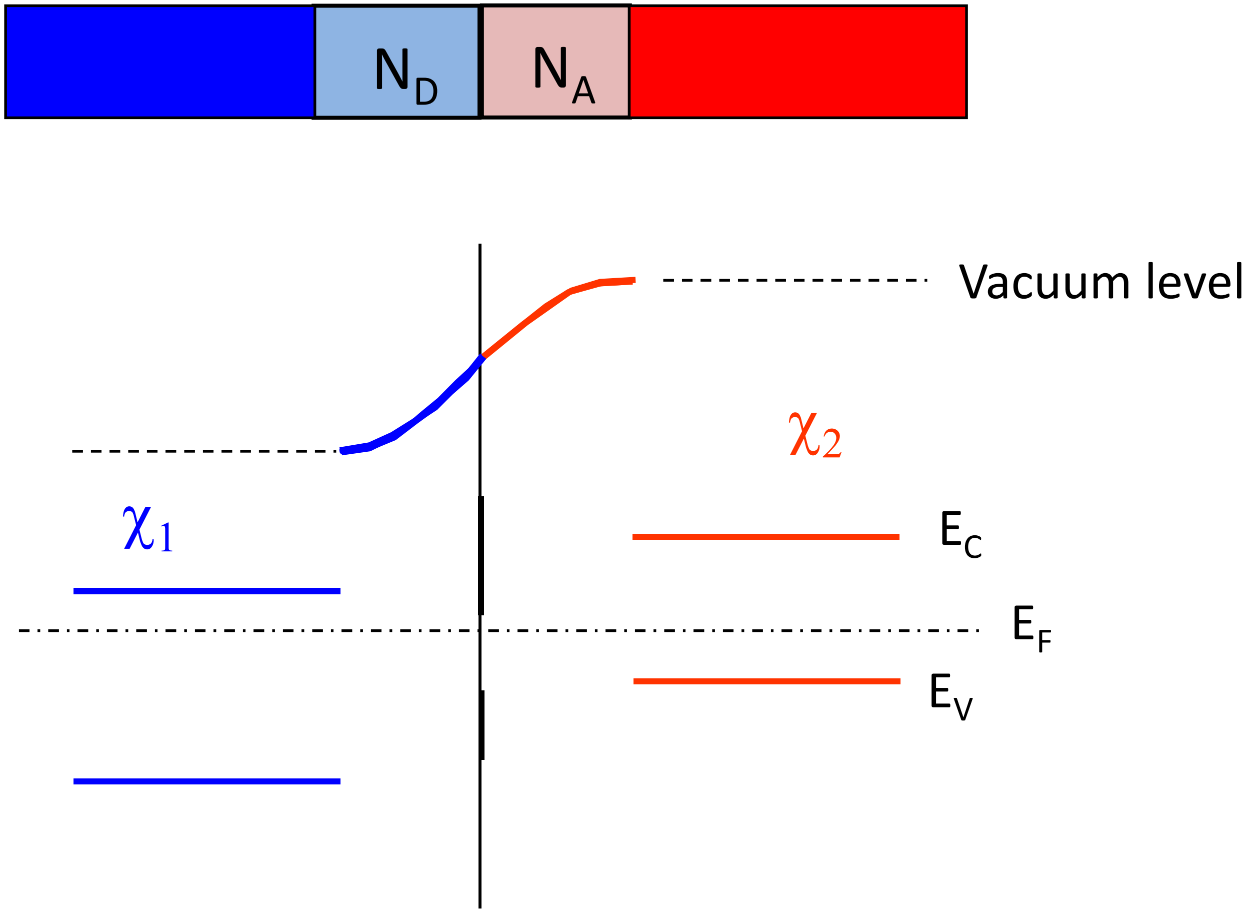
P-$Al_{0.3}Ga_{0.7}As$: n-GaAs (Type I junctions)

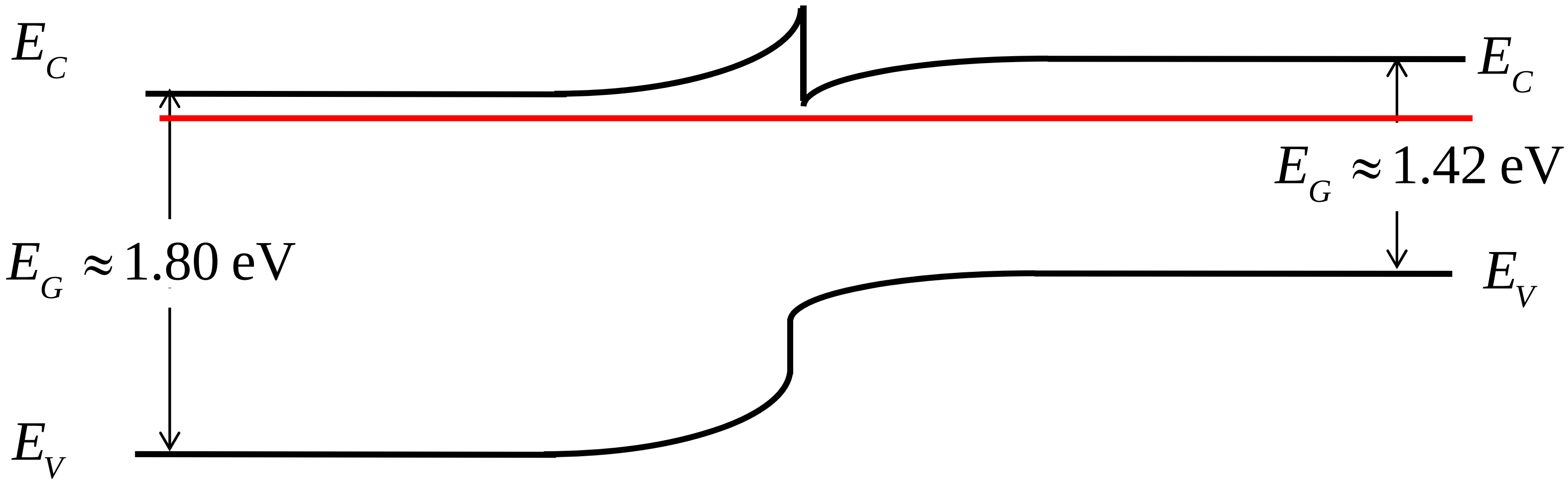


(AlInAs/InP) Type II Junctions



N-Al$_{0.3}$Ga$_{0.7}$As : **n**-GaAs Junctions

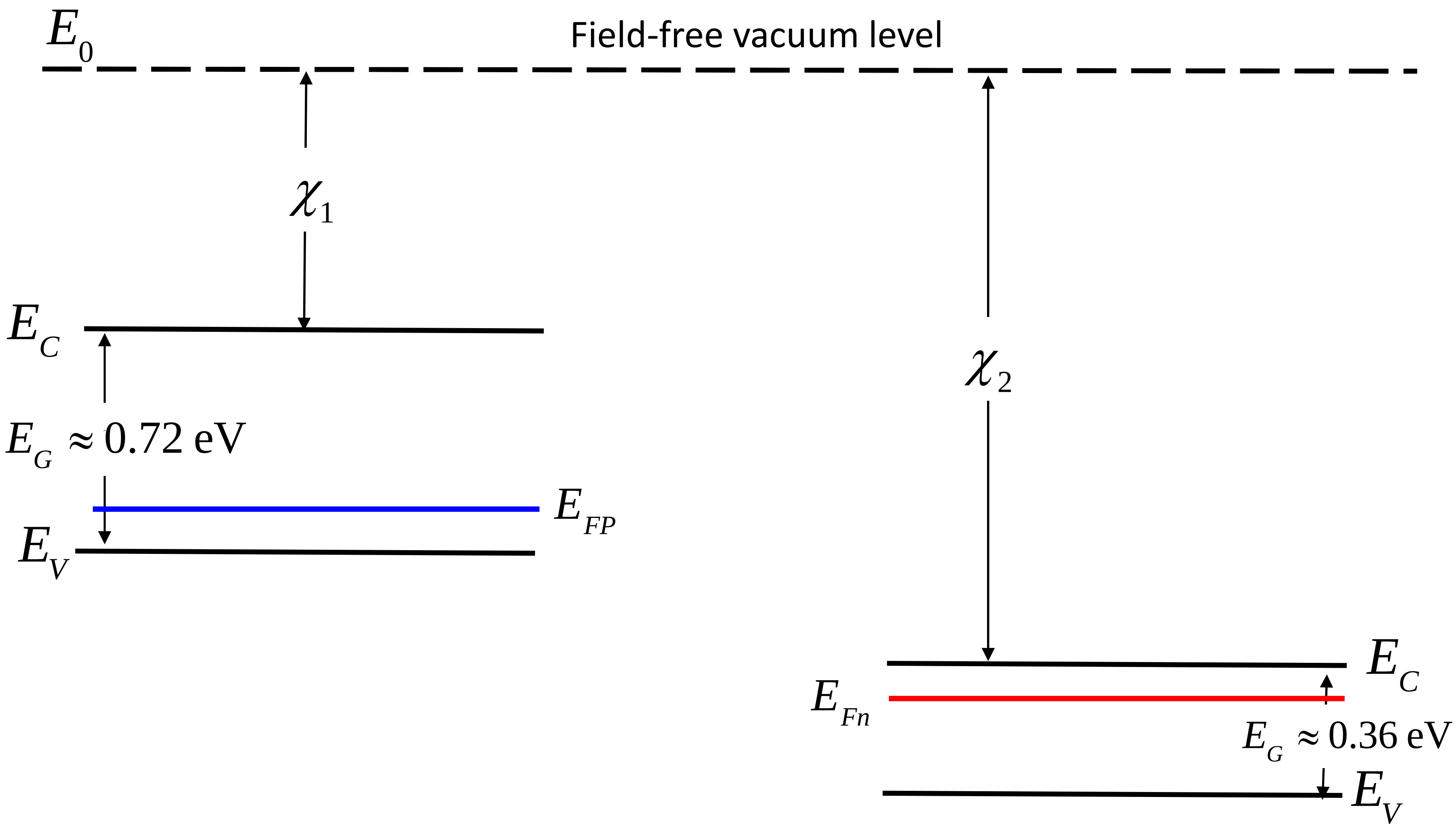
'Isotype Heterojunction'



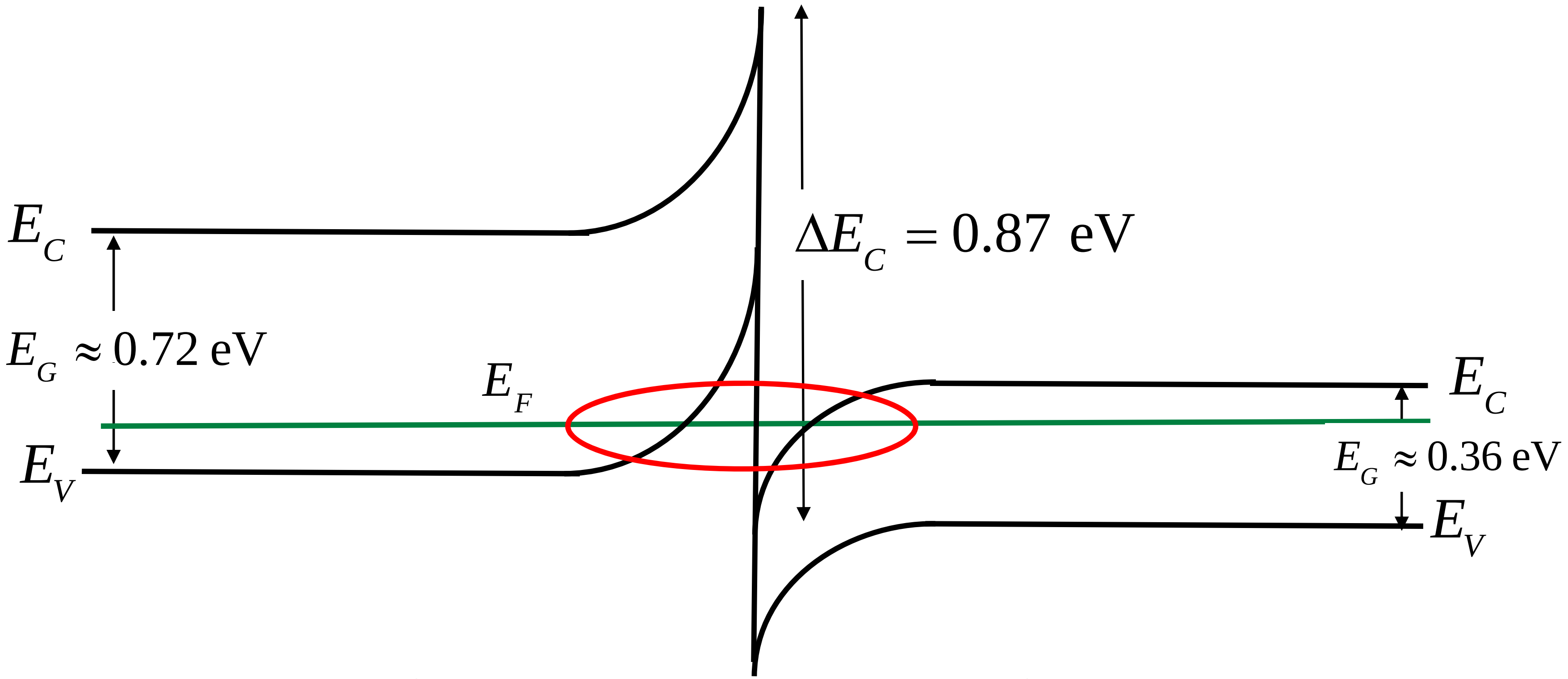
Depletion Layer   Accumulation Layer

Metal-Metal junctions have similar features …

P-GaSb : n-InAs (Type III)



P-GaSb : n-InAs (Type III)



Accumulation Layer! Accumulation Layer!

Conclusion

1. Heterojunction transistors offer a solution to the limitations of poly-Si bipolar transistors.

2. Equilibrium solutions for HBTs are very similar to those of normal BJTs.

3. Depending on the alignment, there could be different types of heterojuctions. Each has different usage.

4. We will discuss current transport in HBTs in the next class.