微电子器件物理
异质结三极管

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2020/12/15

如何设计一个好的三极管

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

→ Graded Base transport

→ Polysilicon Emitter

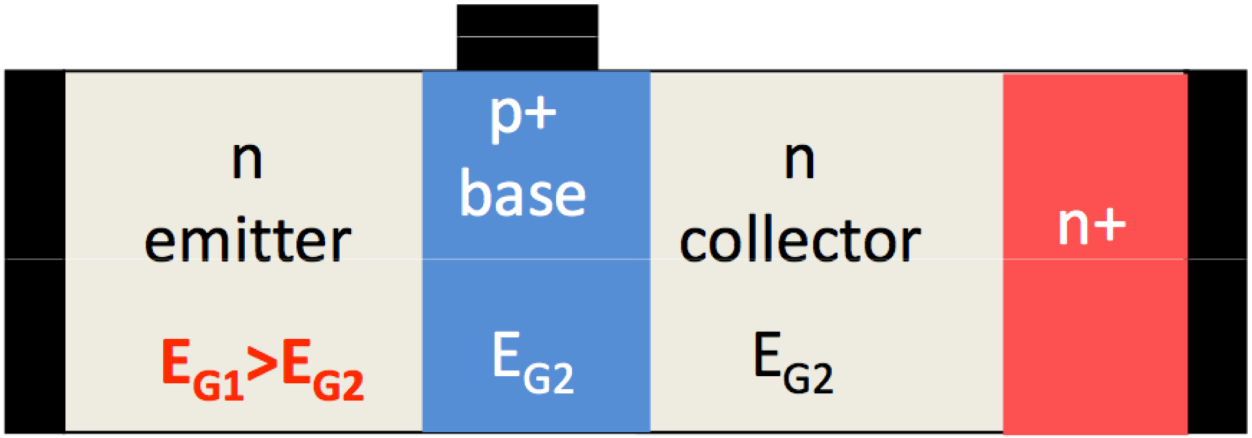
Heterojunction bipolar transistor

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

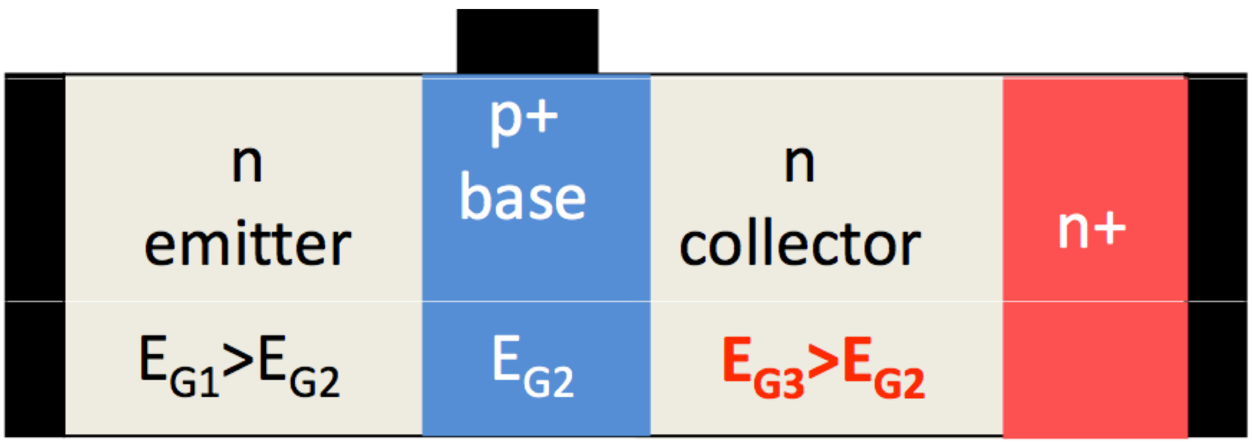
Emitter bandgap > Base Bandgap

异质结三极管

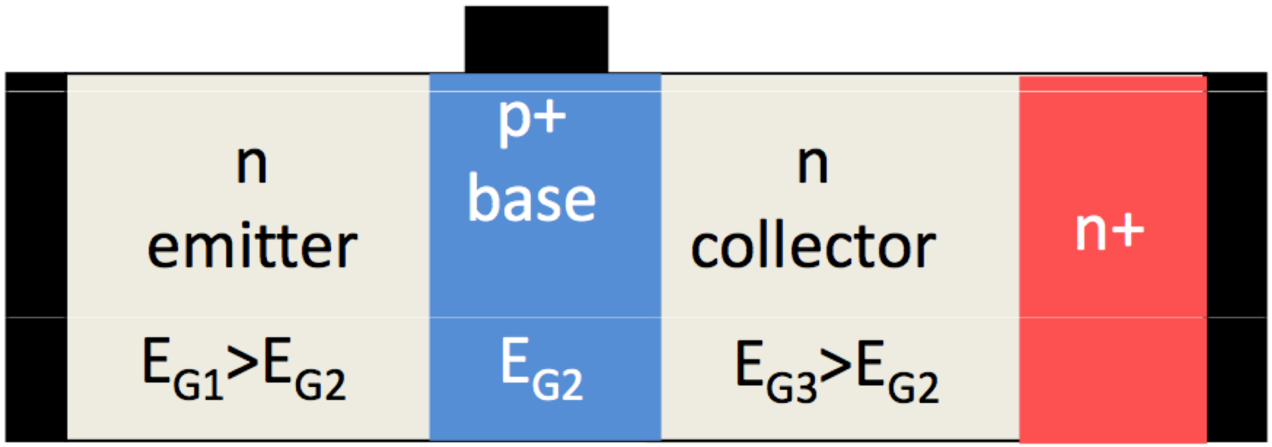
1）宽发射区HBT



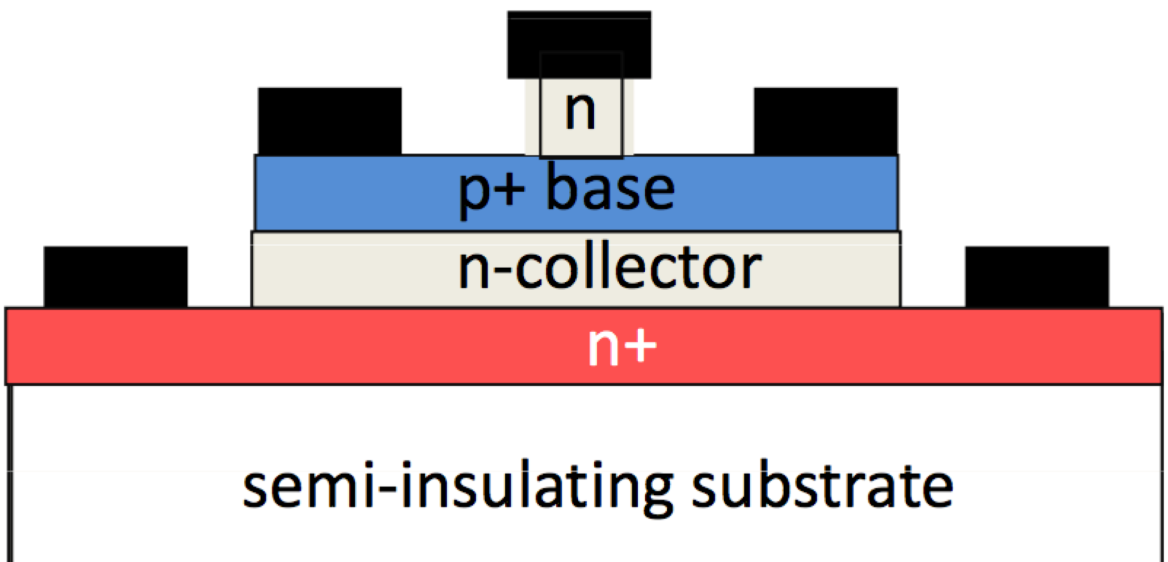
2）双异质结三极管



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

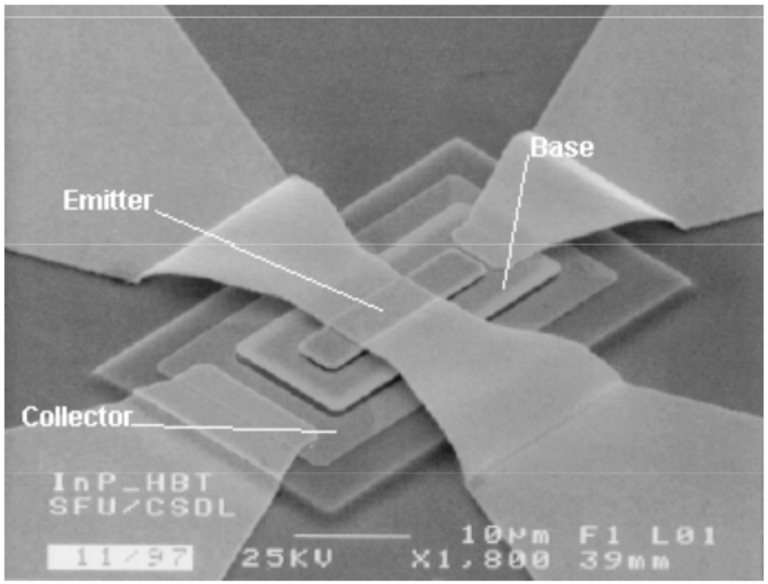
3) **Monolithic, millimeter-wave IC's (MMIC's)**

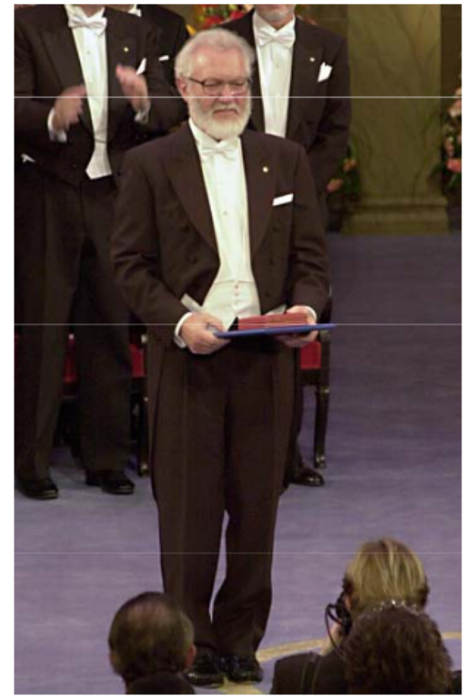
   -front ends for receivers and transmitters

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.

禁带与晶格匹配

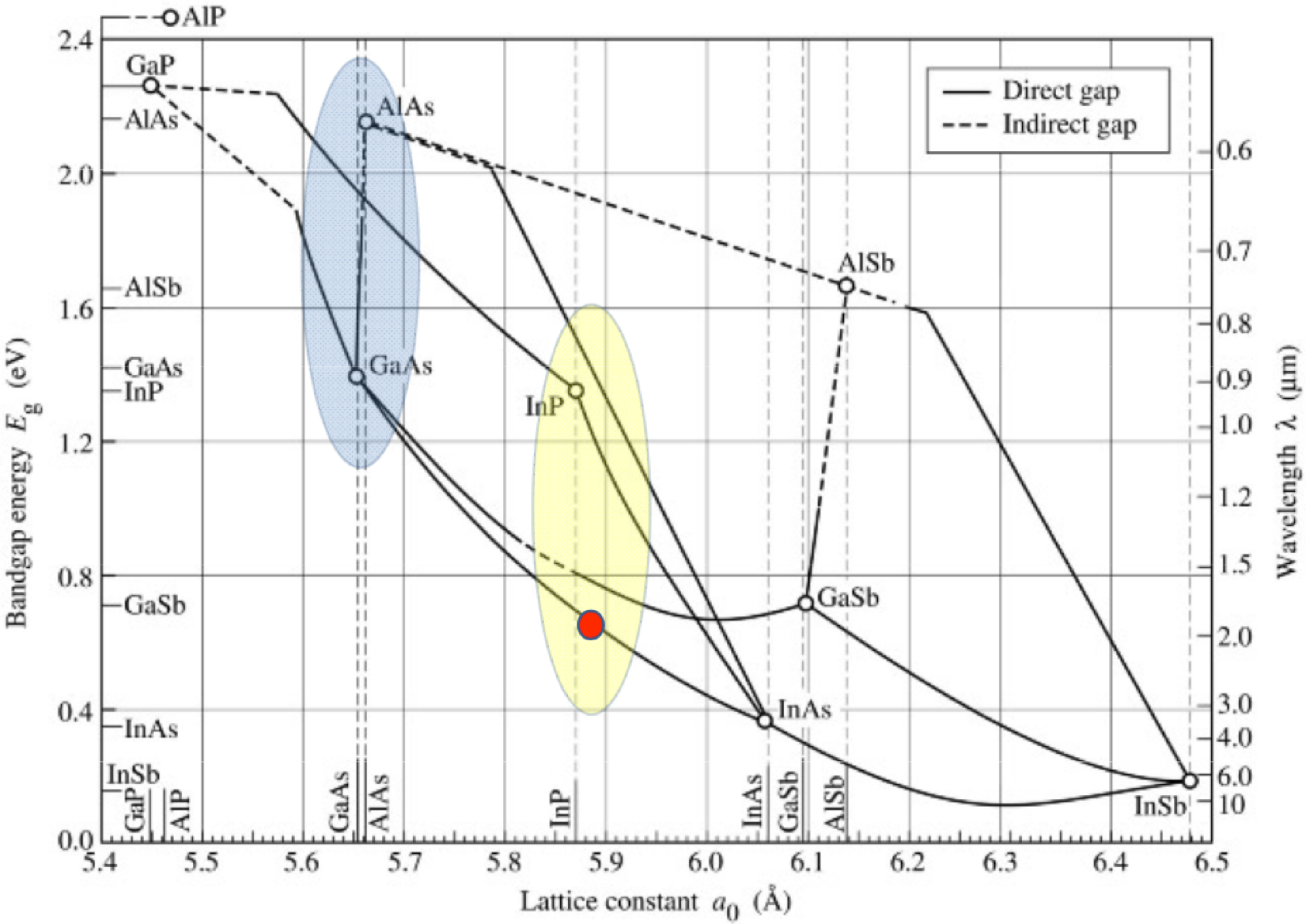
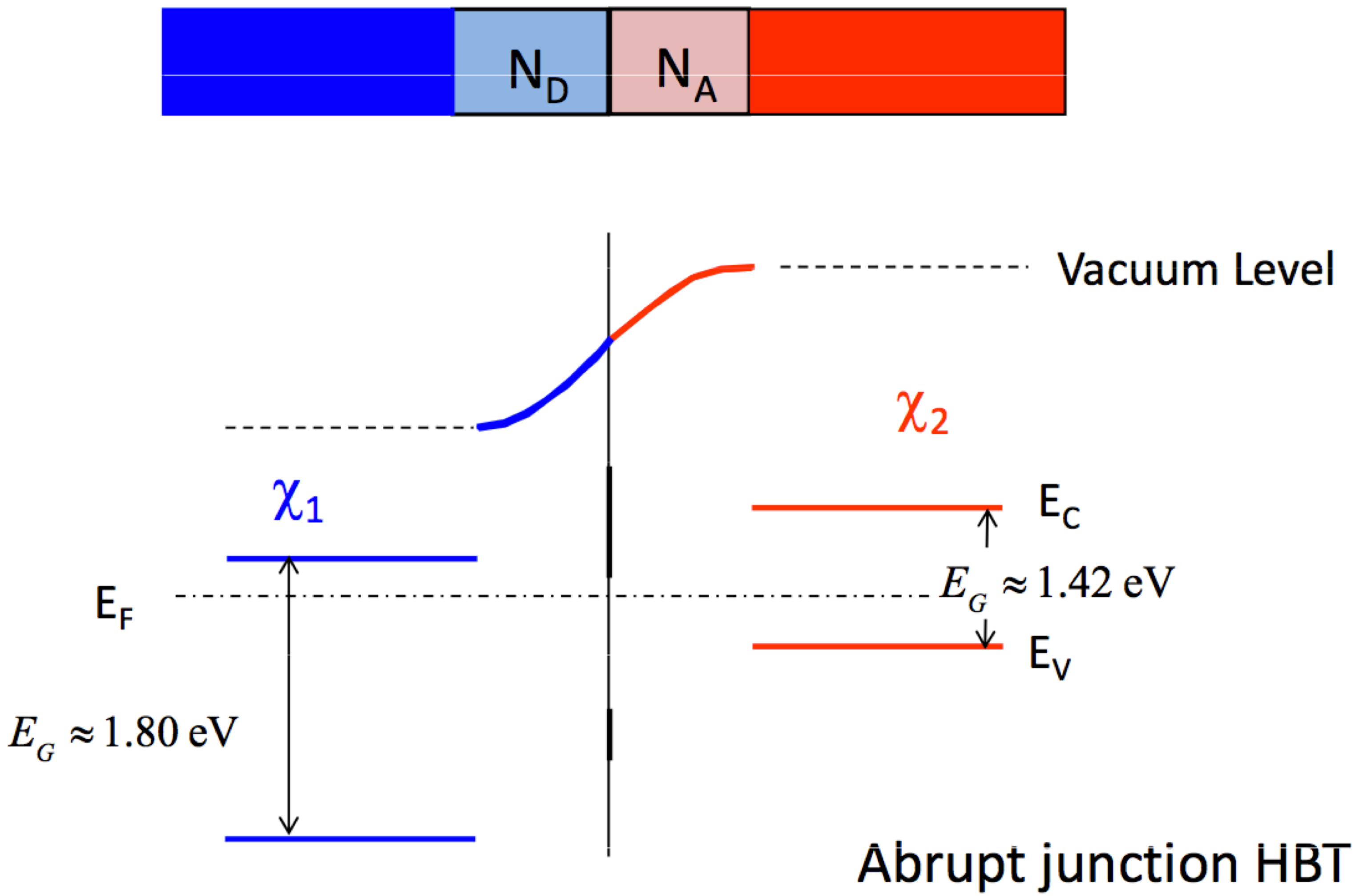


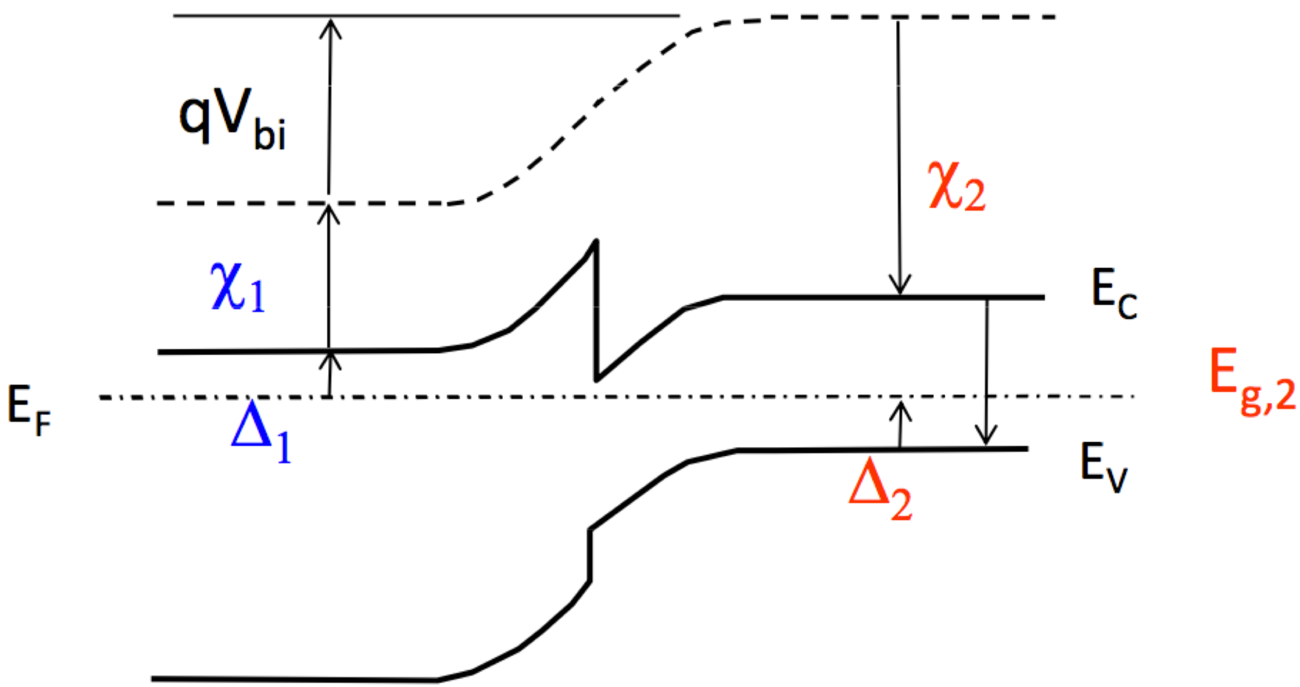
Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

N-$Al_{0.3}Ga_{0.7}As$: p-GaAs (Type-I Heterojunction)



内建势与无穷远处边界条件

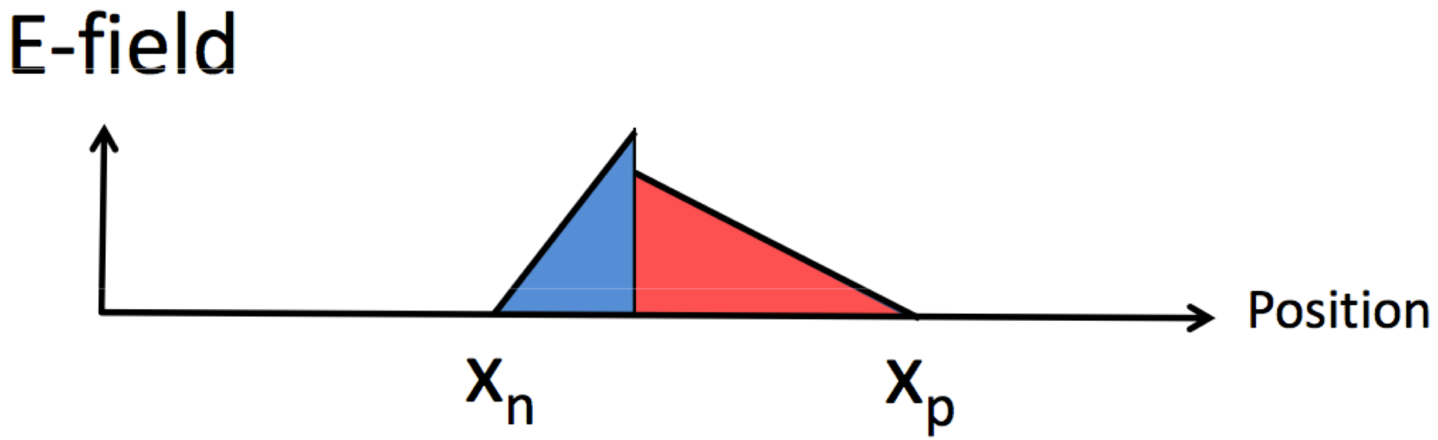
$$\Delta_1 + \chi_1 + qV_{bi} = E_{g,2} - \Delta_2 + \chi_2$$



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

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

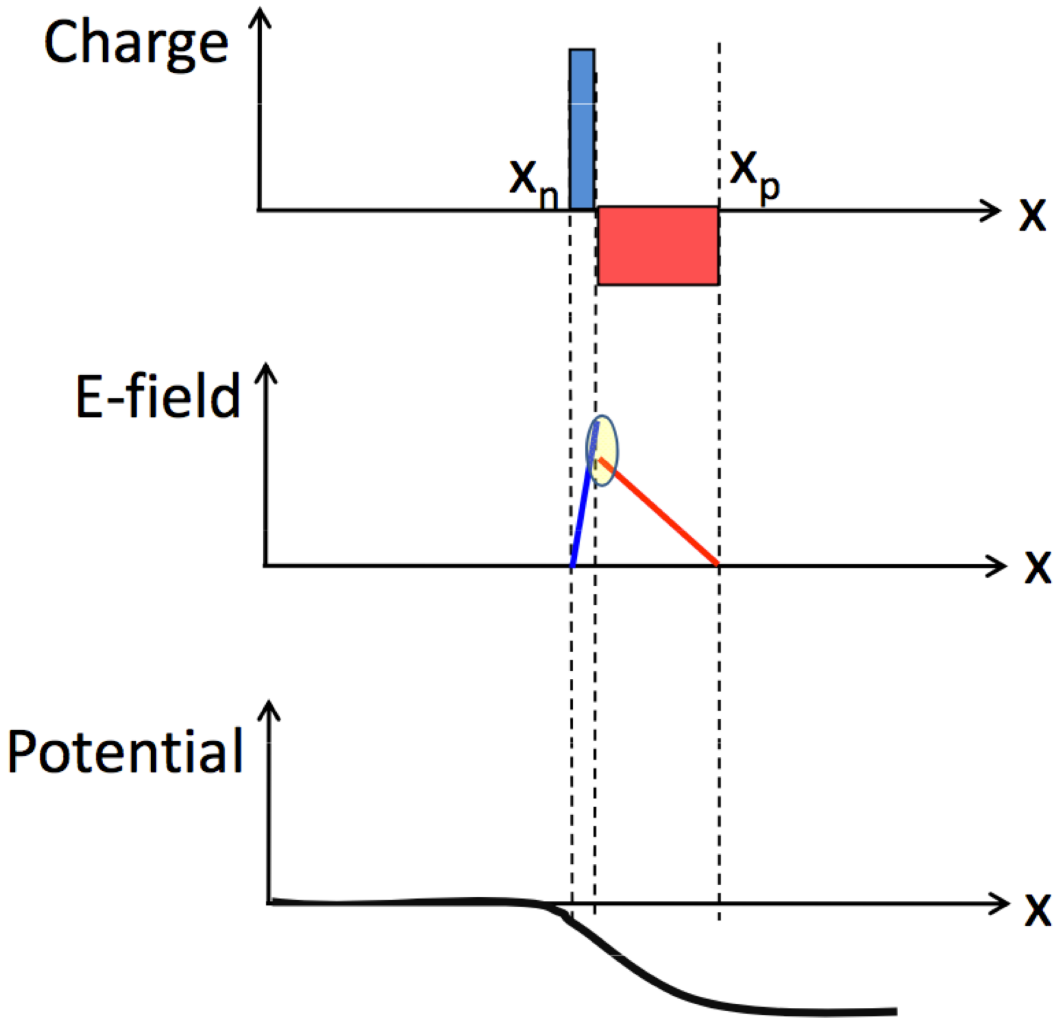
界面处边界条件



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

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

HBT的解析解



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

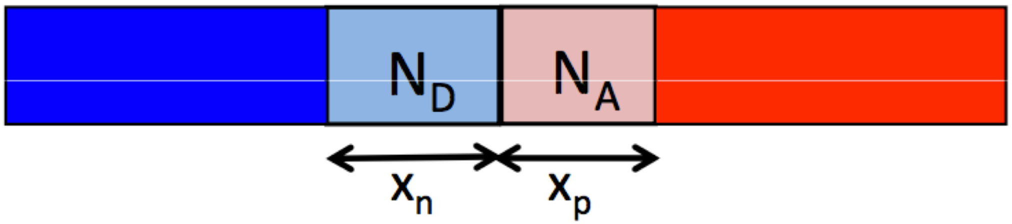
$$E\left(0^+\right)=\frac{qN_A x_p}{k_{s,B}\varepsilon_0}$$

$$\Rightarrow N_D x_n = N_A x_p$$

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

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

耗尽区（空间电荷区）



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

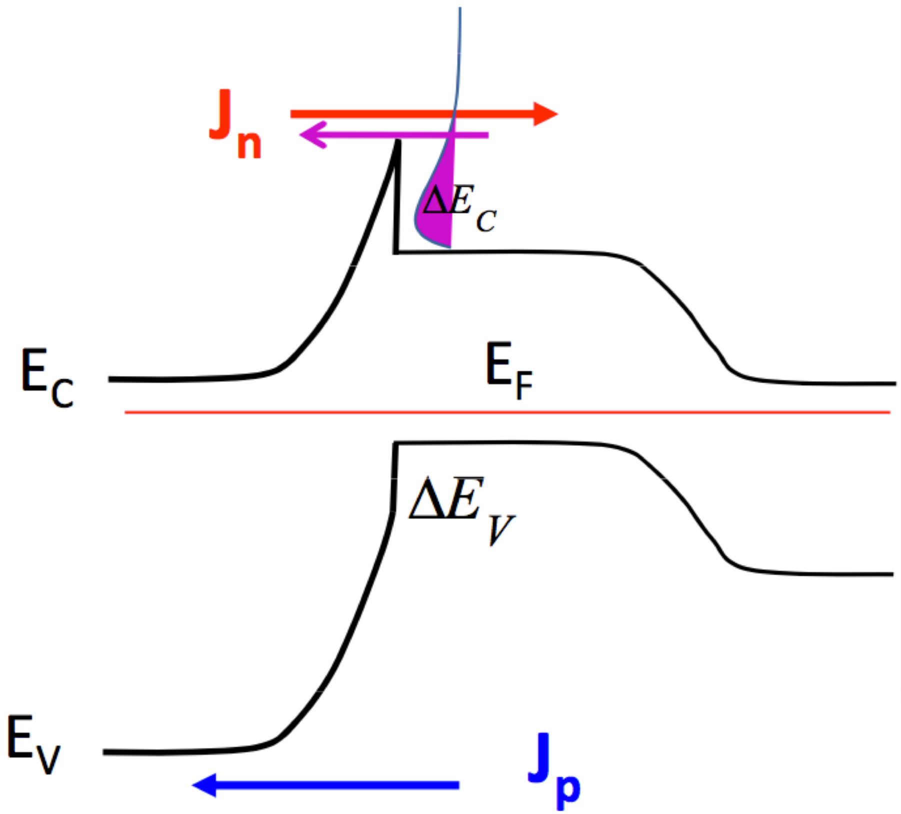
$$V_{bi} = \frac{qN_E x_{n,BE}{}^2}{2\kappa_{s,E}\varepsilon_0} + \frac{qN_B x_{p,BE}{}^2}{2\kappa_{s,B}\varepsilon_0}$$

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

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

突变结HBT

$$J_{n,B\to E} = q\left(\frac{n_{iB}^2}{N_B}\right)\upsilon_{Rp}e^{-\Delta E_C/k_BT} = J_n(V_{BE}=0)$$



$$J_n = q\left(\frac{n_{iB}^2}{N_B}\right)\upsilon_{Rp}e^{-\Delta E_C/k_BT}e^{qV_{BE}/k_BT}$$

$$J_p = q\left(\frac{n_{iE}^2}{N_E}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\beta = \frac{N_E}{N_B}\frac{\upsilon_{Rp}}{\left(D_p/W_E\right)}\left[\frac{n_{iB}^2}{n_{iE}^2}e^{-\Delta E_C/k_BT}\right]$$

$$\beta = \frac{N_{DE}}{N_{AE}}\frac{\upsilon_{Rp}}{\left(D_p/W_E\right)}e^{\Delta E_V/k_BT}$$

Gain in abrupt npn BJT defined only by valence band discontinuity!

如何进一步提高增益?

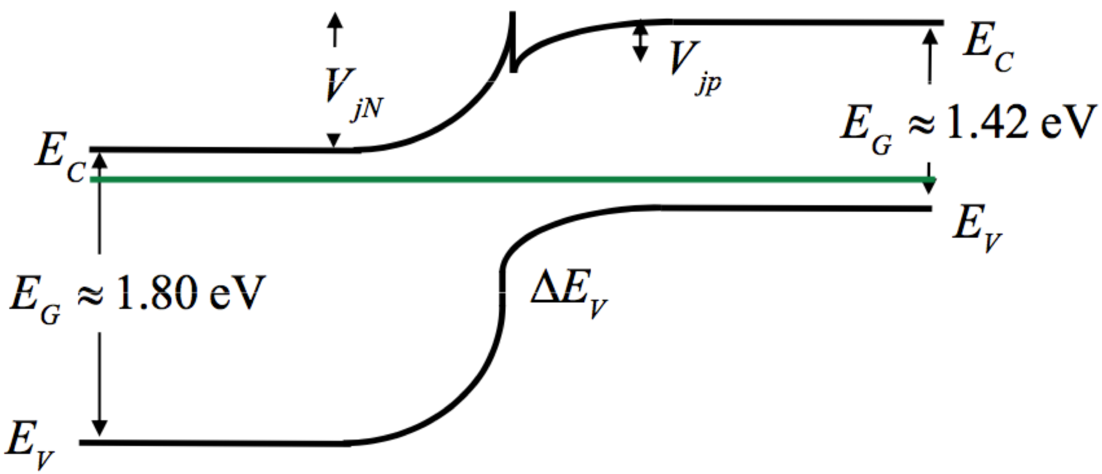
$$\beta \rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{D_p / W_E} \sim \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{D_p / W_E} e^{(\Delta E_g)\beta}$$

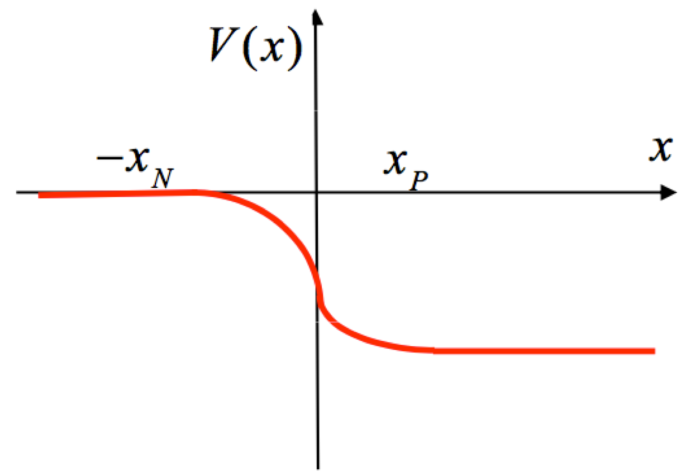
$$\beta = \frac{N_E}{N_B} \frac{\upsilon_{R,p}}{\left(D_p / W_E\right)} e^{\Delta E_V / k_B T}$$

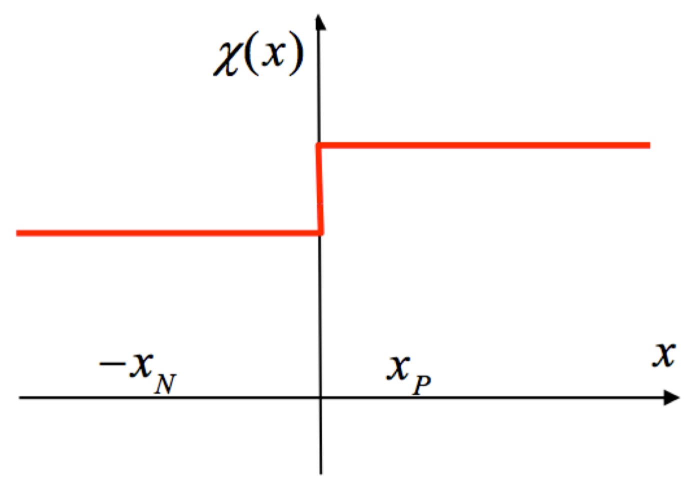
Abrupt junction HBT

为了提高增益，使用缓变结**HBT**

突变结



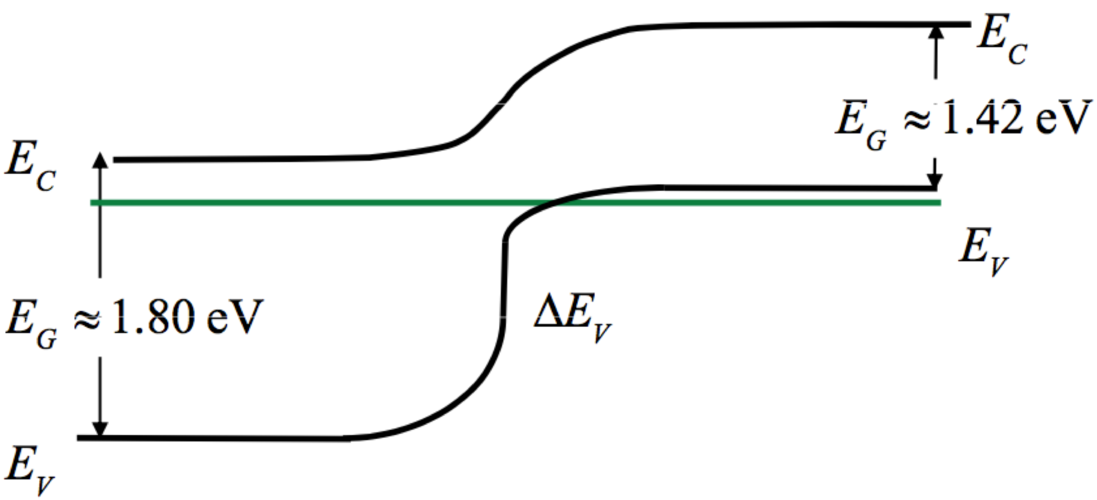


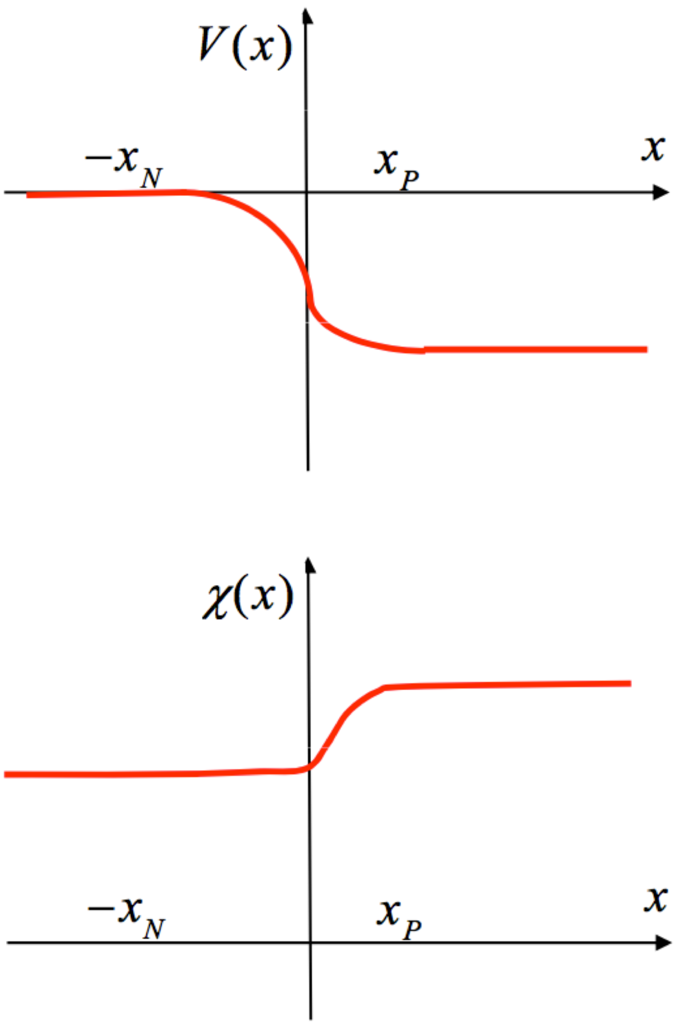


$$E_C(x) = E_0 - \chi(x) - qV(x)$$

$$E_V(x) = E_C(x) - E_G(x)$$

缓变结

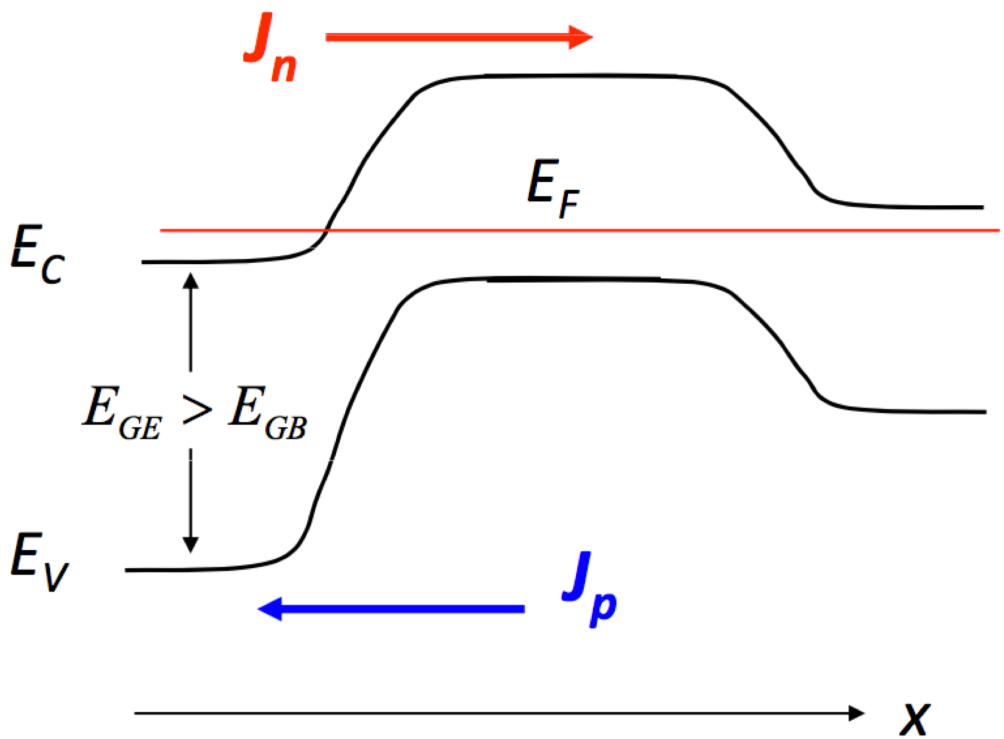




$$E_C(x) = E_0 - \chi(x) - qV(x)$$

$$E_V(x) = E_C(x) - E_G(x)$$

电流增益



No exponential Suppression!

$$J_n = q\left(\frac{n_{iB}^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

$$J_p = q\left(\frac{n_{iE}^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\beta = \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}\frac{n_{iB}^2}{n_{iE}^2}$$

$$n_i = \sqrt{N_C N_V}e^{-E_G/2k_BT}$$

$$\beta \approx \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}e^{\Delta E_G/k_BT}$$

HBT的优点：反转基区掺杂

$$\beta_{DC} \approx \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} e^{\Delta E_G / k_B T}$$

1) Thin Base for high speed

2) Very heavily doped Base to prevent Punch Through, reduce Early effect, and to lower R_{ex}

3) Moderately doped Emitter (lower $C_{j,BE}$)

"inverted base doping" $N_{AB} >> N_{DE}$

如何设计一个好的三极管

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

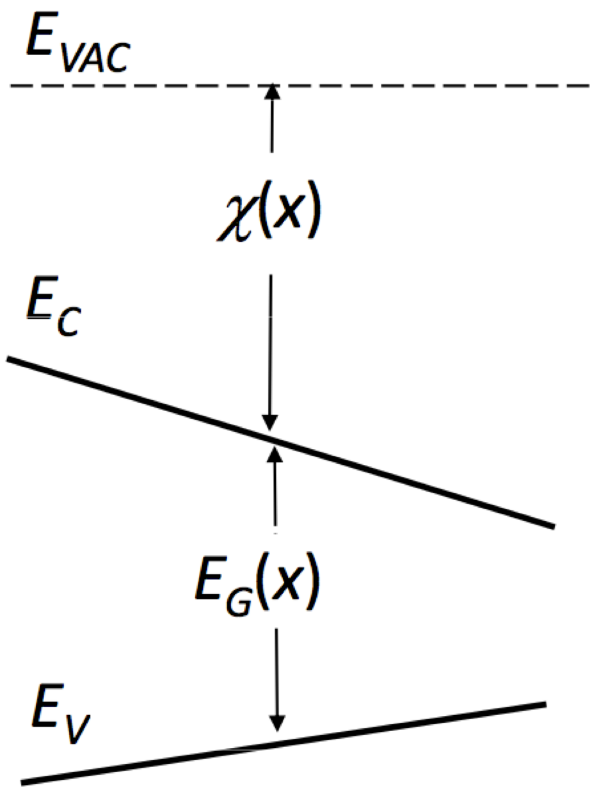
Graded Base transport

Polysilicon Emitter

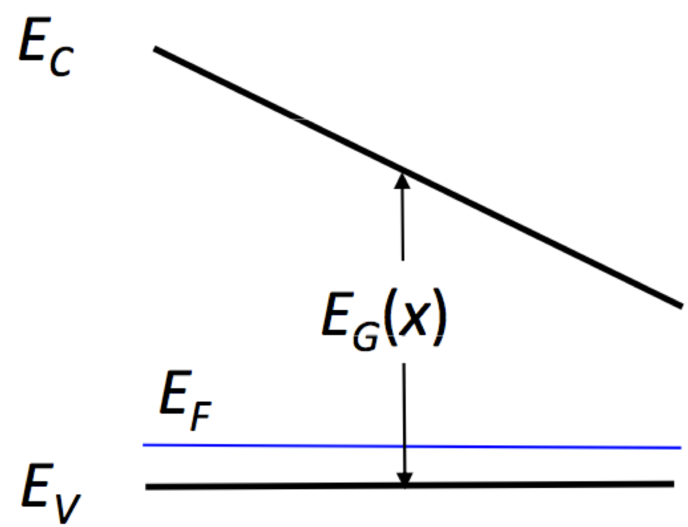
Heterojunction bipolar transistor

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

Graded Bases

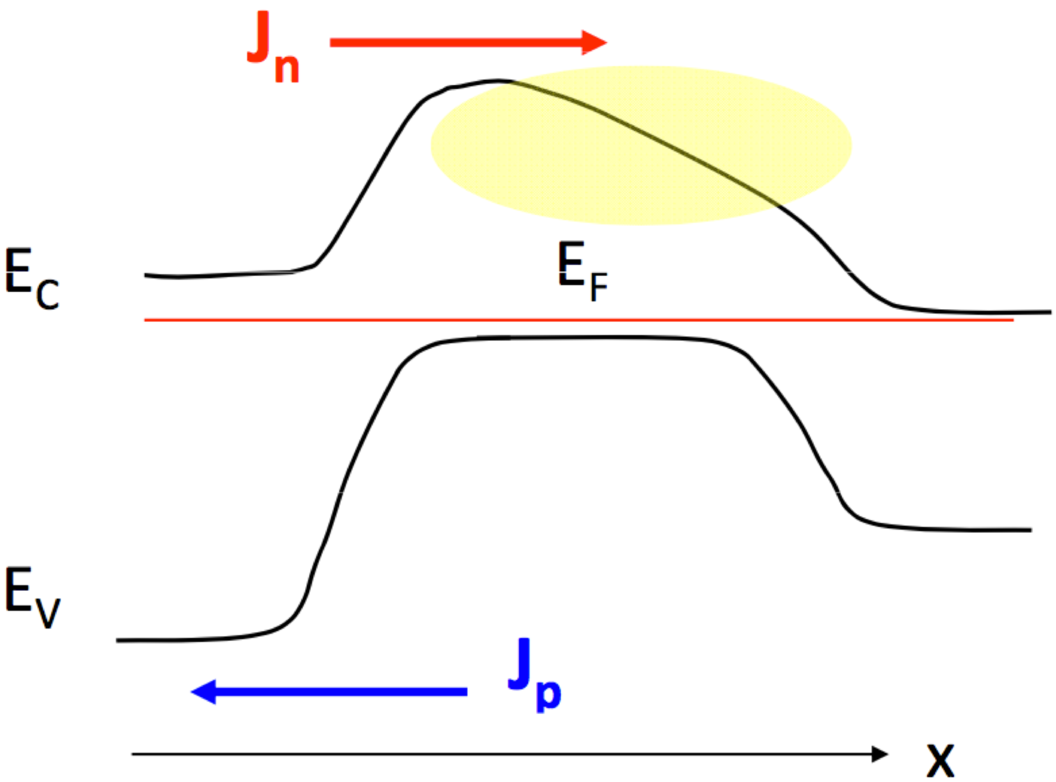


Intrinsic
compositionally graded



Uniformly p-doped
compositionally graded

Graded Base HBTs



$$J_n = q\left(\frac{\overline{n}_{iB}^2}{N_B}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

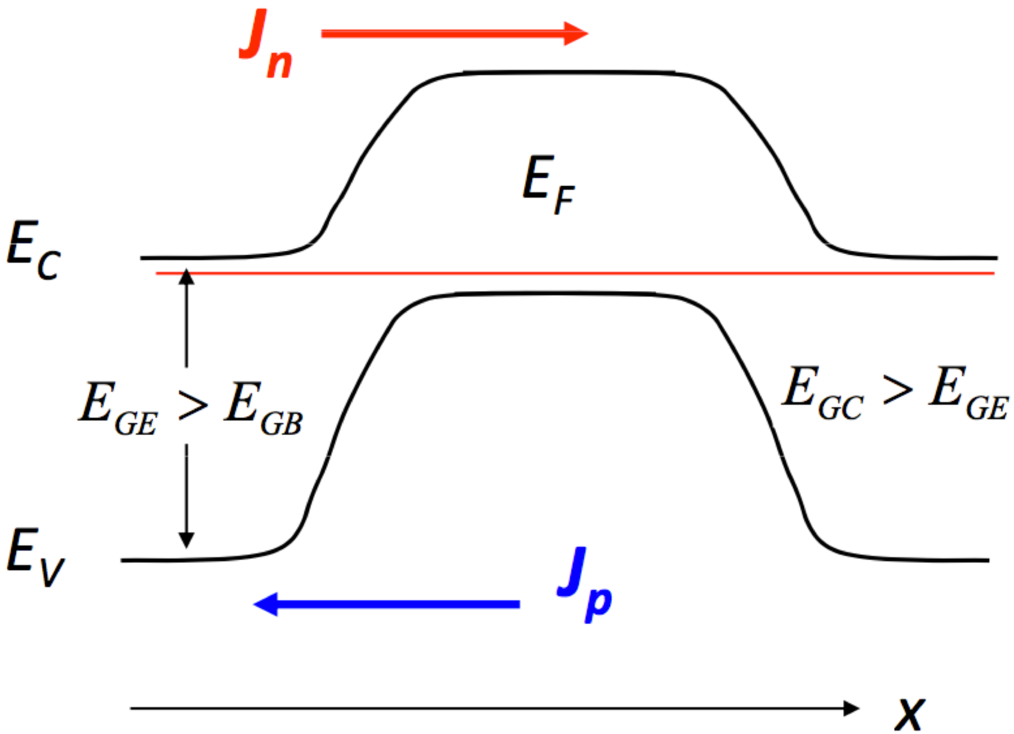
$$J_p = q\left(\frac{n_{iE}^2}{N_E}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\beta_{DC} = \frac{N_E}{N_B}\frac{D_n}{D_p}\frac{W_E}{W_B}\frac{\overline{n}_{iB}^2}{n_{iE}^2}$$

$$\tau_b = \frac{W_B}{\mu_n \mathcal{E}_{eff}} << \frac{W_B^2}{2D_n}$$

$$\mathcal{E}_{eff} = \frac{\Delta E_G/q}{W_B}$$

双异质结三极管

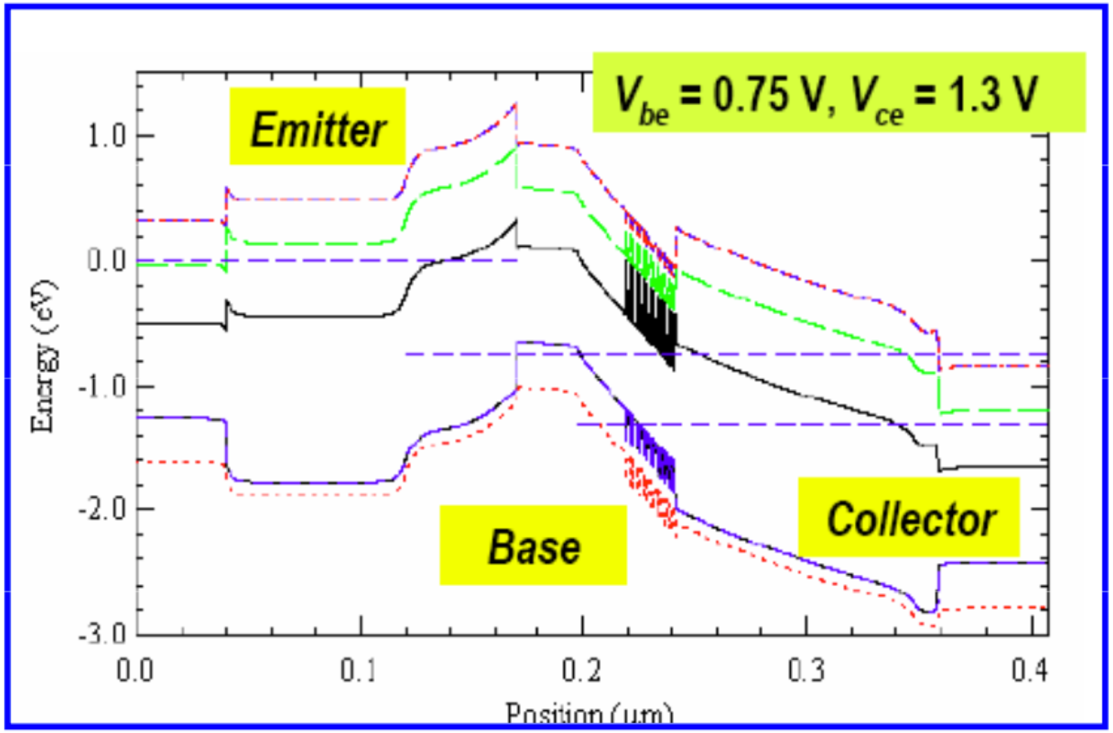


- Symmetrical operation
- No charge storage when the b-c junction is forward biased
- Reduced collector offset voltage
- Higher collector breakdown voltage

外延层设计

DHBT: Abrupt InP emitter, InGaAs base, InAlGaAs C/B grades

InGaAs 3E19 Si 400 Å
InP 3E19 Si 800 Å
InP 8E17 Si 100 Å
InP 3E17 Si 300 Å
InGaAs 8E19 → 5E19 C 300 Å
Setback 3E16 Si 200 Å
Grade 3E16 Si 240 Å
InP 3E18 Si 30 Å
InP 3E16 Si **1030** Å
InP 1.5E19 Si 500 Å
InGaAs 2E19 Si **125** Å
InP 3E19 Si **3000** Å
SI-InP substrate

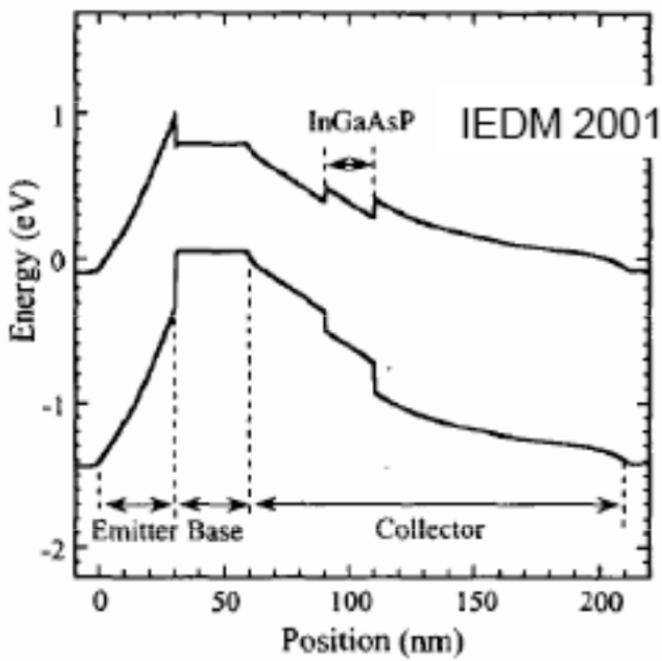


外延层设计

InGaAs/InGaAsP/InP grade

InP/InGaAs DHBTs with 341-GHz f_T at high current density of over 800 kA/cm^2

Minoru Ida, Kenji Kurishima, Noriyuki Watanabe, and Takatomo Enoki



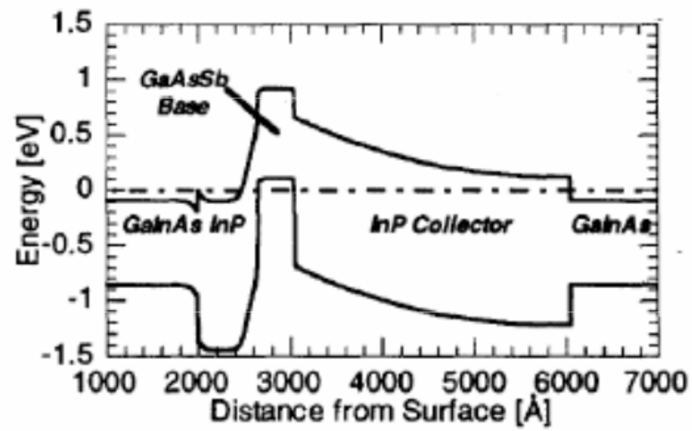
-suitable for MOCVD growth
- excellent results

InP/GaAsSb/InP DHBT

11th International Conference on Indium Phosphide and Related Materials
16-20 May 1999 Davos, Switzerland
TuA1-3

InP/GaAsSb/InP DOUBLE HETEROJUNCTION BIPOLAR TRANSISTORS WITH HIGH CUT-OFF FREQUENCIES AND BREAKDOWN VOLTAGES

N. Matine, M. W. Dvorak, X. G. Xu, S. P. Watkins, and C. R. Bolognesi



- does not need B/C grading
- E/B band alignment through
  GaAsSb alloy ratio (strain)
  or InAlAs emitter
- somewhat poorer transport parameters
  to date for GaAsSb base

Thanks!
Q&A