Heterojunction Bipolar Transistor (HBT)

A vertical device that has been used in many applications is called the HBT. The p-type base creates a barrier for electron diffusion from the n-type emitter to the n-type collector. One of the advantages of this electronic device is that the base thickness can be made too short and therefore the transient time for the electrons to tunnel through the base is very short.

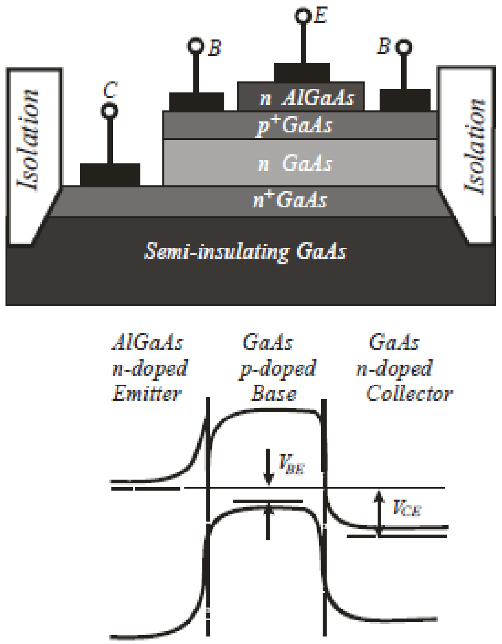


Fig. 6.18. A schematic structure for a GaAs/AlGaAs HBT is shown with the emitter (E), base (B), and collector (C). The energy band diagram is also sketched showing the base emitter voltage (V_{BE}) and collector emitter voltage (V_{CE}).

Heterojunction Bipolar Transistor (HBT)

The formalism of the transport properties of HBTs is similar to that encountered in the bipolar transistor. The collector current density is given by

$$J_c = \frac{D_n e n_{po}}{W_B}\left(e^{eV_{BE}/k_B T} - 1\right)$$

where V_{BE} is the base–emitter voltage, n_{po} is the equilibrium electron density in the base (minority-carrier density), D_n is the electron diffusion coefficient, and W_B is the base width. For $eV_{BE} \gg k_B T$, the transconductance can be obtained as

$$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{e}{k_B T} I_C$$

The exponential dependence of g_m on V_{BE} produces large transconductance values, which are advantageous for digital applications.

The capacitance due to the minority charge stored in the base is given by

$$C = \frac{\partial Q_B}{\partial V_{BE}} = \frac{e}{k_B T}\frac{e n_p W_B}{2}$$

Heterojunction Bipolar Transistor (HBT)

where n_p is the minority-carrier density at the base entrance. The time required for the electron to travel through the base, τ_{tr}, can be obtained as

$$\tau_{tr} = \frac{W_B}{\upsilon_d} = \frac{W_B}{2D_n/W_B} = \frac{W_B^2}{2D_n}$$

where the average diffusion velocity is taken as $\upsilon_d = 2D_n/W_B$.

The time defined can be drastically reduced by minimizing the base width leading to a very high speed device.

In the GaAs/AlGaAs HBTs, the aluminum mole fraction in the emitter material is usually kept to >30%. Carbon is usually used as the dopant in the p-type GaAs base material. It has a low diffusion coefficient compared to other dopants, such as zinc and magnesium. The dopant diffusion from the base to the emitter causes a significant problem in HBTs. Thus, there is a trade-off between the doping level and the performance of the device. HBTs have been fabricated from other semiconductor systems, such as Si/SiGe and InGaP/GaAs. The InGaP/GaAs system has a larger valence band offset as compared to the conduction band offset. This is an advantage since the holes see a larger barrier, and hence the hole injection from the base to the emitter is reduced.

Tunneling Hot Electron Transistor (THET)

The presence of potential barriers allows one to fabricate unipolar transistors in which the structure is composed of only n-type layers. The simplest device of this class is called the HET. The tunneling hot electron transistor (THET) is another variation of the HET.

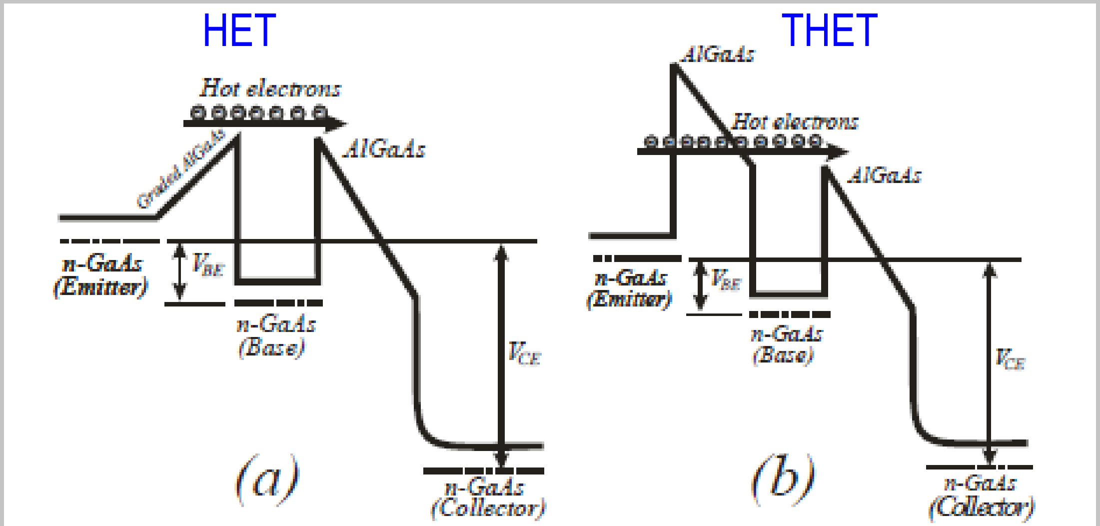
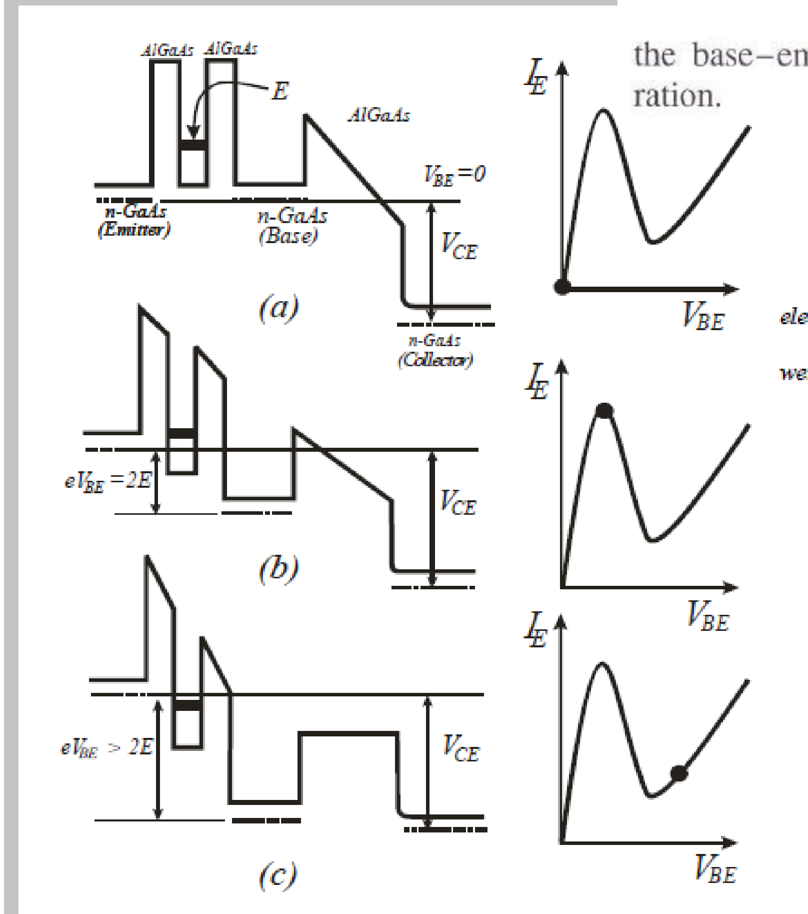


Fig. 6.19. *The conduction energy band diagram is shown for unipolar transistors. (a) Hot electron transistor with graded AlGaAs barrier and (b) a tunneling hot electron transistor.*

These are hot electrons and can ballistically transverse the base region very rapidly, allowing high frequency operation. By varying the base–collector voltage, it is possible to use the second AlGaAs barrier as an analyzer of the energy distribution of the electrons that arrive at the collector terminal.

Resonant Tunneling Hot Electron Transistor (RHET)

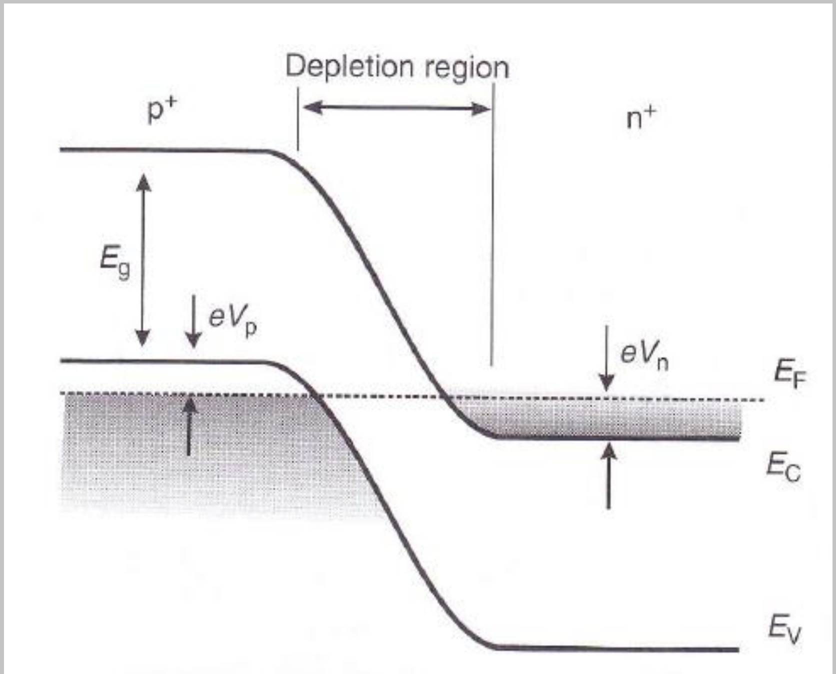


the collector–emitter bias voltage, V_{CE}, is kept constant, while the base–emitter voltage, V_{BE}, is varied. This is a common emitter configuration.

Fig. 6.20. *Conduction energy band diagram of a unipolar resonant tunneling hot electron transistor (RHET) illustrated for a constant V_{CE}. The band diagram and the I-V curves were plotted for (a) $V_{BE}=0$, (b) $eV_{BE}=2E$, and (c) $eV_{BE}>2E$.*

The application of RHETs can be realized in digital electronics and logic circuits. For example, if two inputs, A and B, are connected to the base, the output will be high (transistor is off) if both A and B are low or high. Otherwise, the output is low (transistor is on). This is an exclusive NOR logic circuit.

p-n Junction Tunneling Transistor



A sketch of a typical band diagram of a p–n junction tunneling diode.

The current of the tunneling diode is composed of three components (Sze, 1981): the tunneling, excess, and thermal currents. At thermal equilibrium, the tunneling current from the valence band to the conduction band ($I_{v \to c}$) and the

p-n Junction Tunneling Transistor

current from valence conduction band to the valence band ($I_{c \to v}$) are balanced and they can be expressed as

$$I_{c \to v} = A \int_{E_c}^{E_v} f_c(E) n_c(E) T_t (1 - f_v(E)) n_v(E) \mathrm{d}E$$

$$I_{v \to c} = A \int_{E_c}^{E_v} f_v(E) n_v(E) T_t (1 - f_c(E)) n_c(E) \mathrm{d}E.$$

where A is a constant, $f_c(E)$ and $f_v(E)$ are Fermi–Dirac distribution functions, $n_c(E)$ and $n_v(E)$ are the density of states in the conduction and valence bands, and T_t is the tunneling probability (transmission coefficient), which is taken as

$$T_t = \exp\left(-\frac{\pi \sqrt{m^*} E_g^{3/2}}{2\sqrt{2} e \hbar \mathcal{E}}\right) \exp\left(-\frac{2E_\perp}{\overline{E}}\right)$$

where E_g is the band gap of the semiconductor, $\mathcal{E}$ is the built-in electric field, $E_\perp$ the energy associated with the momentum perpendicular to the direction of the tunneling, and

$$\overline{E} = 4\sqrt{2} e \hbar \mathcal{E} / (3\pi m^* E_g^{1/2})$$

p-n Junction Tunneling Transistor

which is a measure of the significant range of transverse momentum. $\overline{E}$ is usually small, which means that only electrons with small transverse momentum can tunnel. When a bias voltage is applied to the p–n junction, the observed tunneling current (I_t) is

$$I_t = I_{c\to v} - I_{v\to c} = A\int_{E_c}^{E_v}[f_c(E) - f_v(E)]T_t n_c(E) n_v(E)\mathrm{d}E$$

The tunneling current in the above equation is derived by Demassa *et al*. and is simplified according the following expression:

$$I_t = I_0^p \frac{V}{V_0^p}\exp\left(1 - \frac{V}{V_0^p}\right)$$

where I_0^p and V_0^p are the peak current and peak voltage defined in Fig. 6.22.

p-n Junction Tunneling Transistor

V_0^p was determined by Demassa *et al*. to be $V_0^p = (V_n + V_p)/3$ where V_n and V_p are the degeneracy voltages defined in Fig. 6.21.

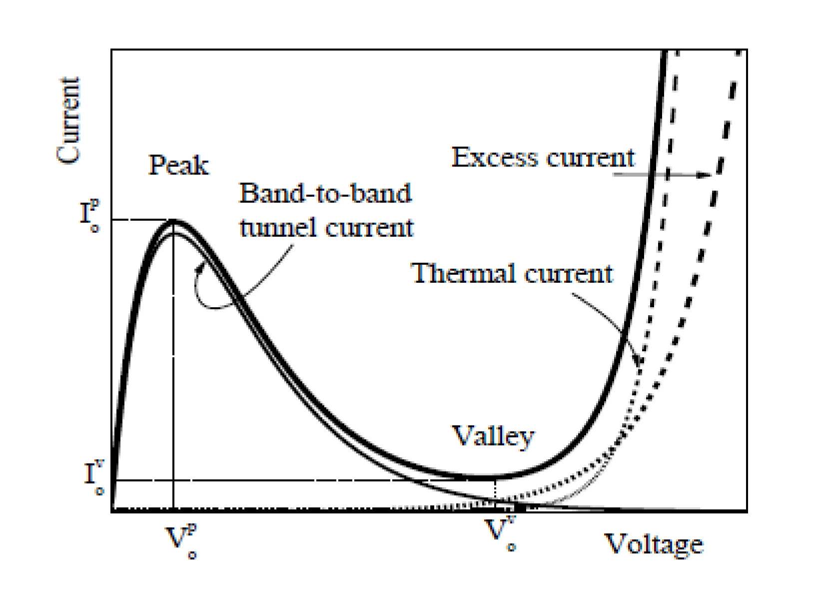


Fig. 6.22. *Static current-voltage characteristics of a typical tunnel diode. The current is composed of three components: band-to-band tunnel current, excess current, and thermal current. The sum of the three current is shown as the thick curve with the well known peak and valley.*

p-n Junction Tunneling Transistor

The excess current is mainly due to defect-assisted tunneling, in which the carriers tunnel through defect states in the band gap. This component of the total

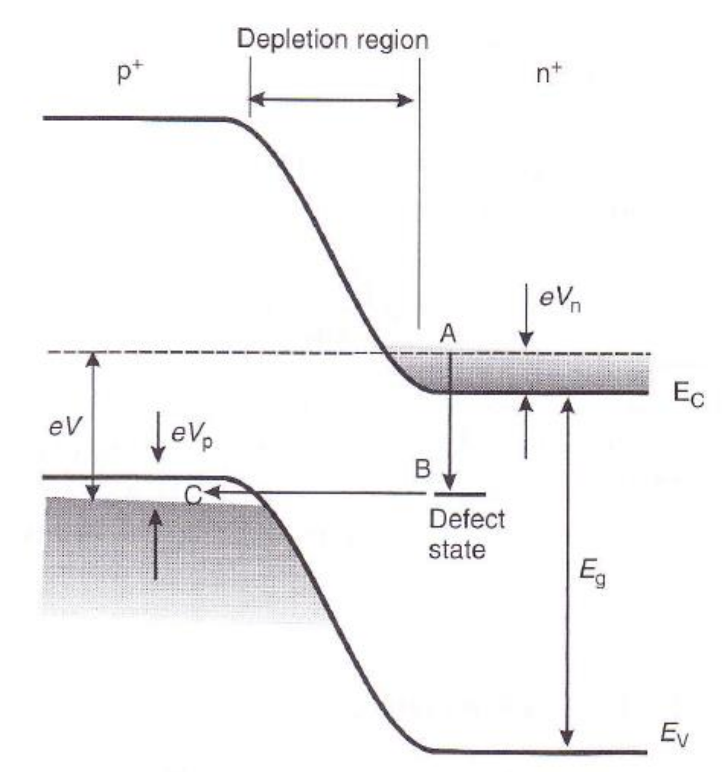


FIGURE 6.23 A sketch of the p–n junction band gap showing the defect-assisted tunneling, which causes the excess current under high bias voltage.

p-n Junction Tunneling Transistor

an electron to tunnel from the conduction band to the valence band. For a bias voltage, V, the energy (E_x) that the electron must have to tunnel is given by

$$E_x \approx E_\mathrm{g} - eV + e(V_\mathrm{n} + V_\mathrm{p}) \approx e(V_\mathrm{bi} - V)$$

where V_bi is the built-in potential.

The tunneling probability is

$$T_x \simeq \exp\left(-\frac{4}{3}\frac{\sqrt{2\mathrm{m}^*}}{\hbar e \mathcal{E}} E_x^{3/2}\right) \simeq \exp\left(-\frac{\alpha_x}{\mathcal{E}} E_x^{3/2}\right)$$

where $\alpha_x \simeq 4\sqrt{2\mathrm{m}^*}/(3\hbar e)$ and $\mathcal{E}$ is the electric field. The electric field across a step function can be written as $\mathcal{E} = 2(V_\mathrm{bi} - V)/W$, where W is the depletion region width given by

$$W = \left[\frac{2\mathcal{E}_0}{e}\left(\frac{N_\mathrm{a} + N_\mathrm{d}}{N_\mathrm{a} N_\mathrm{d}}\right)(V_\mathrm{bi} - V)\right]^{1/2}$$

where ϵ_0 is the permittivity, N_a is the concentration of acceptors, and N_d is the concentration of donors.

p-n Junction Tunneling Transistor

The current density, J_x, associated with the excess current process can be written as

$$J_x \simeq A D_x T_x$$

where D_x is the volume density of the occupied levels at energy E_x above the top of the valence band and A is a constant.

$$J_x \simeq A_1 D_x \exp[-\alpha_x'(E_g - eV + 0.6(V_n - V_p))]$$

where A_1 is a constant. This relation shows that the excess current depends on the density of states and the applied voltage. Equation can be rewritten as (Roy)

$$J_x \simeq J_V \exp\left[-\frac{4}{3}\sqrt{\frac{m^*\epsilon_0}{N^*}}(V - V_0^V)\right] \simeq J_V \exp(A_2(V - V_0^V))$$

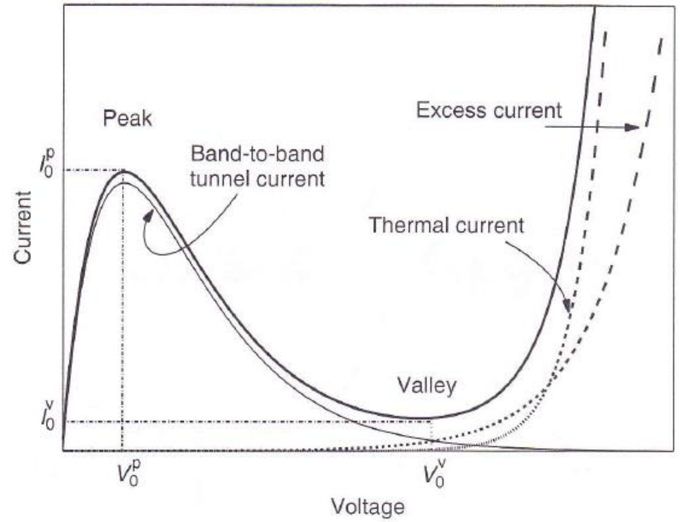
where J_V is the valley current density, V_0^V is the valley voltage, A_2 is a constant and $N^* = N_a N_d/(N_a + N_d)$. Equation is plotted as the long dashed curve in Fig. 6.22.

p-n Junction Tunneling Transistor

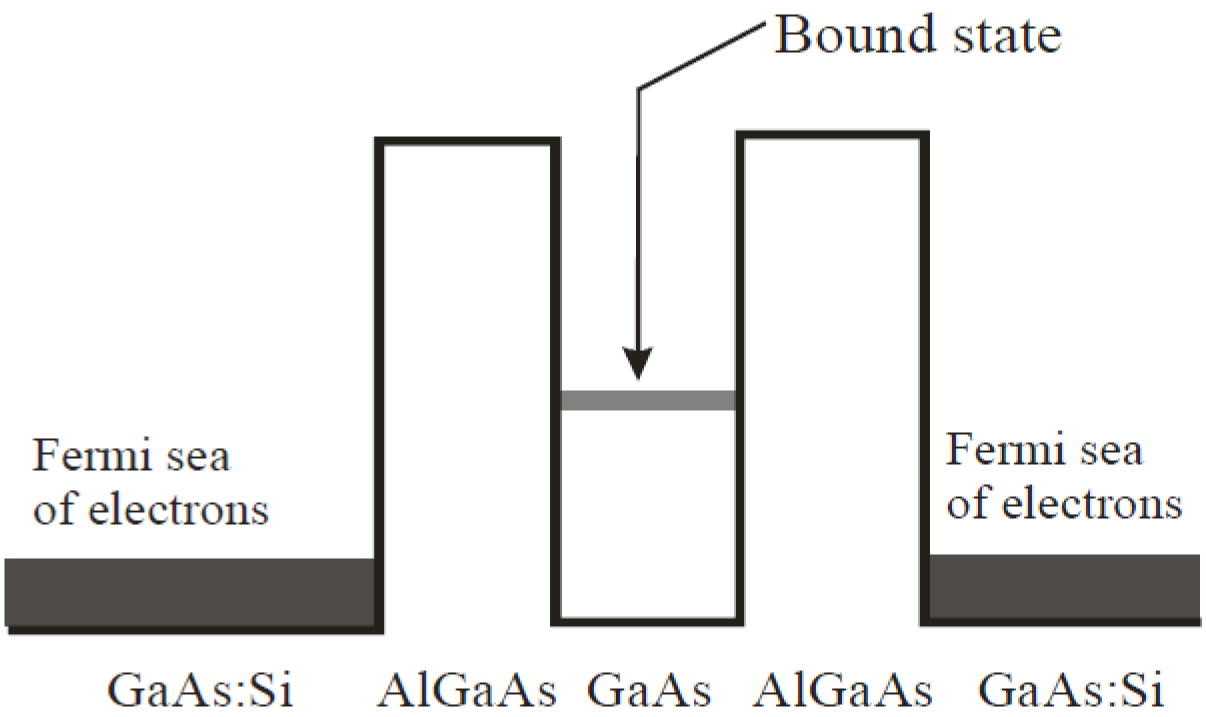
Finally, the third component of the tunneling diode current density is the minority-carrier injection current given by

$$J_{\text{th}} = J_0 \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right]$$

where J_0 is the reverse saturation current density, k_B is the Boltzmann constant, and T is the temperature. The thermal current density is plotted as the short dashes in Fig. 6.22. The sum of the three currents is plotted in this figure as the thick curve which shows the characteristic peak and valley encountered in tunneling diodes.



Resonante Tunnel Diode (RTD)



Resonante Tunnel Diode (RTD)

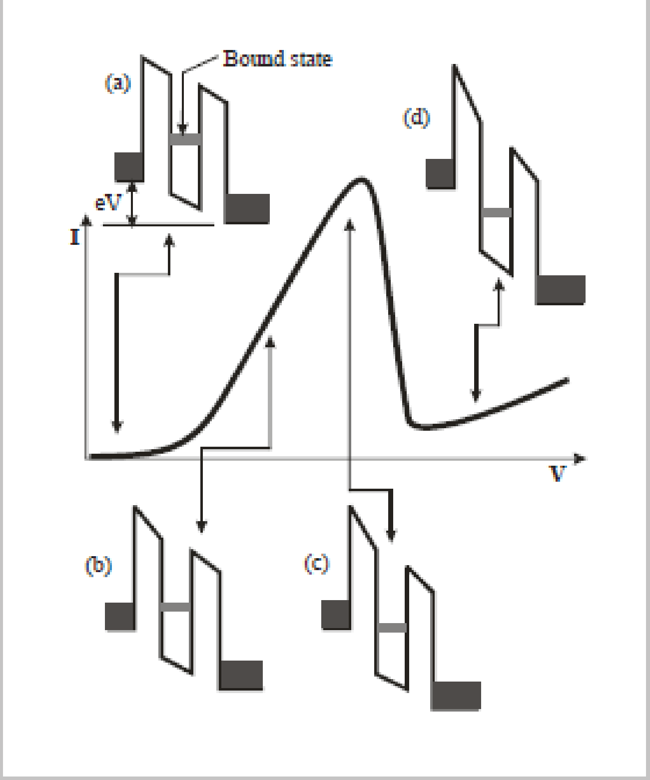


Fig. 6.25. *The I-V characteristic of the resonant tunneling diode with a single bound state is sketched as a function of bias voltage (V).*

Resonante Tunnel Diode (RTD)

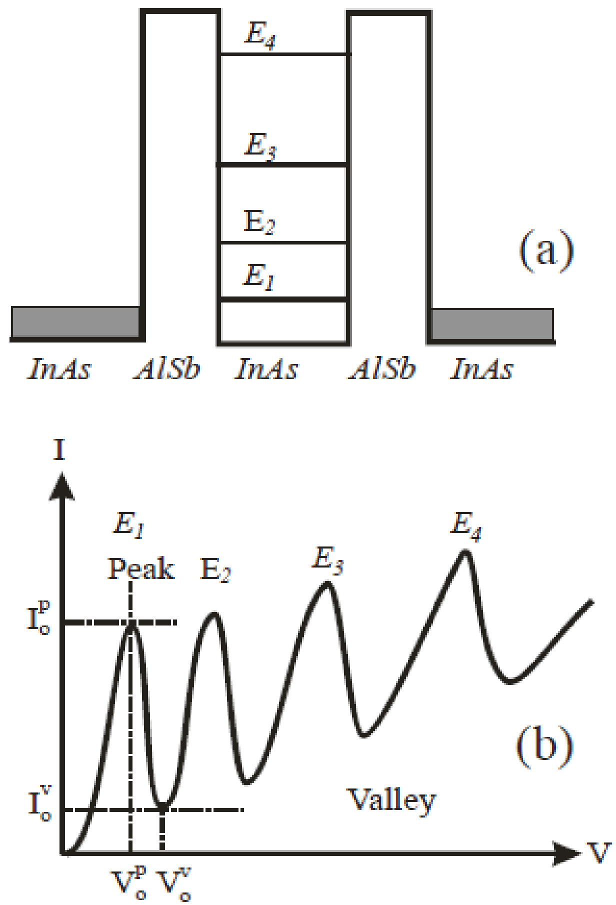


Fig. 6.26. *(a) A sketch of the InAs/AlSb double barrier resonant tunneling diode showing four bound states. (b) A typical I-V characteristic of the tunneling resonant diode showing the peak and valley voltages.*

Resonante Tunnel Diode (RTD)

$$J_z = \frac{e^2 V m^* \mathcal{E}_w}{2\pi^2 \hbar^3} \text{for} 2(\mathcal{E}_0 - \mathcal{E}_F) \leq eV \leq 2\mathcal{E}_0$$

The limitation of the resonant tunneling diode is the "valley" current as shown in Fig. 6.22. For device application, particularly in digital circuits, it is desired to have low valley current. In reality, it is difficult to achieve zero valley current, but with creative designs, one can reduce the valley current to an acceptable value. One possible design is proposed by Kitabayashi *et al*., which is based on InAs/AlSb/GaSb structure as shown in Fig. 6.28a. The structure in this figure is called *resonant interband tunneling diode*.

Double Barrier Resonante Tunnel Diode (DBRTD)

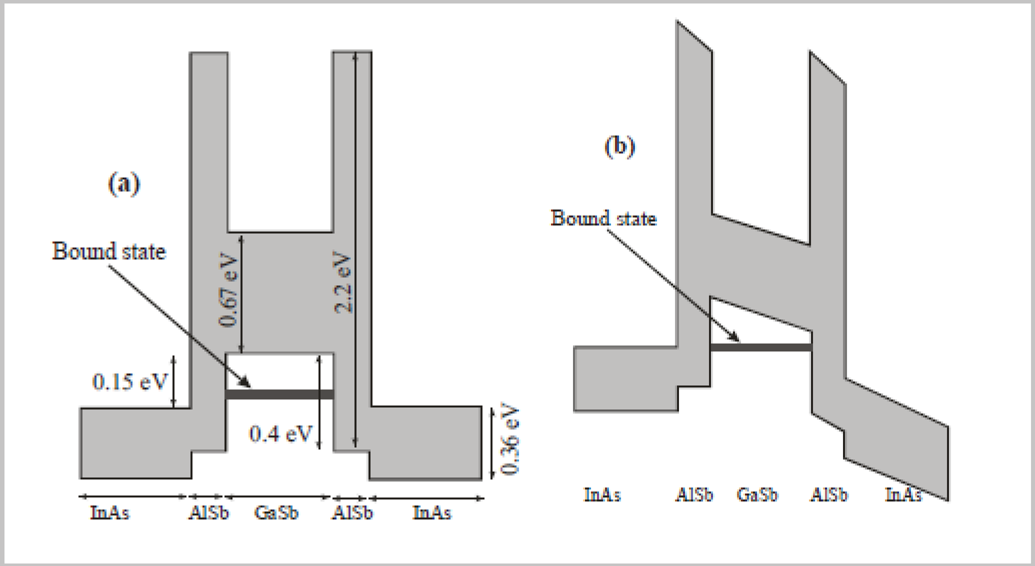


Fig. 6.28. *A schematic band-edge diagram of InAs/AlSb/GaSb,AlSb/InAs double barrier resonant interband tunneling diode under zero bias voltage (a) and with non-zero bias voltage(b).*