Using Quasi-Fermi-Level device analysis 2

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Earlier we showed that QFL analysis was able to reduce the competitive duality of drift-diffusion transport to a simpler and singular drift-only transport due to the gradient in QFL. Then a detailed calculation of diffusion was performed where QFL gradient was non-zero.

In this part, we will review various different situations to show the generality of the QFL description for coarse device analysis (i.e. to show where QFL was flat). Then wherever QFL gradient is non-zero – i.e. the region that blocks current (which is analogous to a pinch-point in a water-pipe), a more detailed calculation is needed. Such a calculation is not limited to drift diffusion but could be almost any mechanism. This adaption to any general mechanism will be shown by two examples (Schottky and BJT) in this section.

Schottky Diode

Drawing the Equilibrium Band Diagram

First, we should be able to draw the band-diagram of a metal-semiconductor junction as shown in Figure 1(a).

1. Before the junction is formed, the vacuum level is flat everywhere. The conduction band, valence band are flat and at fixed levels w.r.t. vacuum level as they are materials properties. This never changes – no matter what bias is applied. The Fermi level of the metal and semiconductor may be discontinuous i.e. flat but at different levels.
2. When the two materials are joined, the Fermi level of the two materials become common and vacuum level has to bend to accommodate this built-in potential at the junction that develops that is exactly equal and opposite to the original fermi-level difference so that ultimately the fermi level is flat after the materials are joined.

   Note: If there is no fermi level difference, then no built-in potential develops (see Figure 1(b)) which is consistent with the above description.

Forming a good metal semiconductor contact – Is it possible?

The metal (say n-type – because its Fermi level is closer to conduction band) will connect with the two bands differently. The metal couples to conduction band well as it supplies electrons easily at high density (Figure 1c). The same can not be said for its coupling with the valence band. It can only supply a very low density of holes. So this metal (n-type) is more strongly coupled to conduction band than valence band.

This begs a question. ***Can a metal electrically connect to (or couple to) both band equally***? Yes, if it has a Fermi level aligned to mid-gap but then it is unable to contact either bands well.

So a metal is normally choses to make good contact with only one of the two bands if current needs to be supplied. So, it can either make a good n-type contact or p-type contact. **So there is nothing called a good general metal semiconductor contact i.e. simultaneously to both bands ☺.**

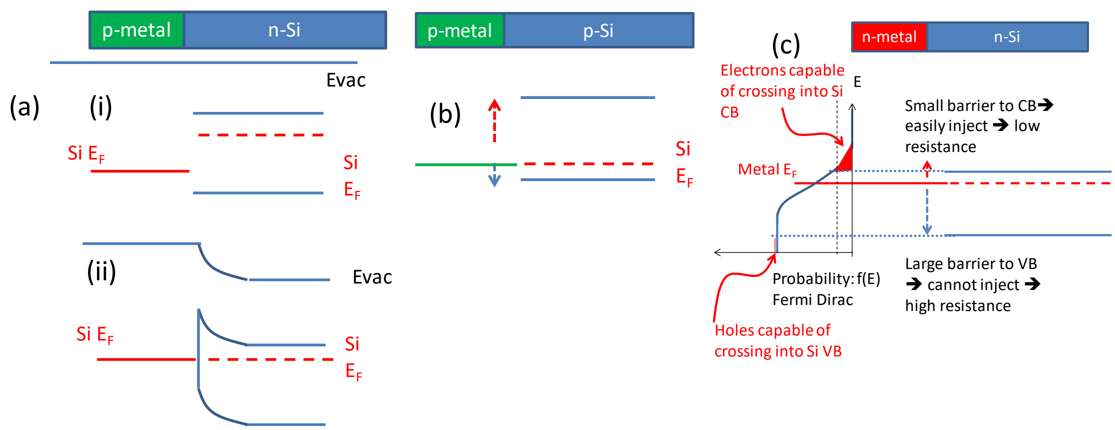


Figure 1 (a) p-type metal contact with n-Si (i) before joining materials (ii) after joining materials. (b) p-metal p-Si contact where miraculously the fermi levels of metal and semiconductor are matched. (c) n-type forms a good contact with conduction band as metal can supply electrons easily (by overcoming the small barrier). However, n-type metal will form equivalently poor contact with valence band as the barrier height is high. We know that electron barrier + hole barrier = band gap. Hence, one cannot improve one without degrading the other.

Application of bias and QFL bending

Step 1 (Electrostatics): Draw Equilibrium band diagram. Find out where voltage will drop i.e. band diagram in forward and reverse bias.

Step 2 (QFL Analysis): Assume equilibrium band diagram. Draw n(x) and p(x) to construct a resistor network. Identify the most resistive region for electron and hole conduction. This is where QFL should drop. We observe that n(x) is lowest at the peak of the barrier for a very small region (δ). On the other hand, the p(x) is low (p_{no}) in the quasi-neutral region in n-type Si – which is substantial (L_p). Thus we know that hole conduction is much more resistive than electron conduction. Hence electron current should dominate.

We can quickly estimate the rough electron vs hole current ratio. Electron current is many orders higher than hole current e.g. $J_n \approx \frac{n_{@peak}}{\delta} \mu_n q V_{app}$ while $J_p \approx \frac{p_{no}}{L_p} \mu_p q V_{app}$; Thus, we need to concentrate on **electron current only at the tip of the barrier**.

Step 3 (Detailed Current computation): We will do this in the next for 2 different scenarios.

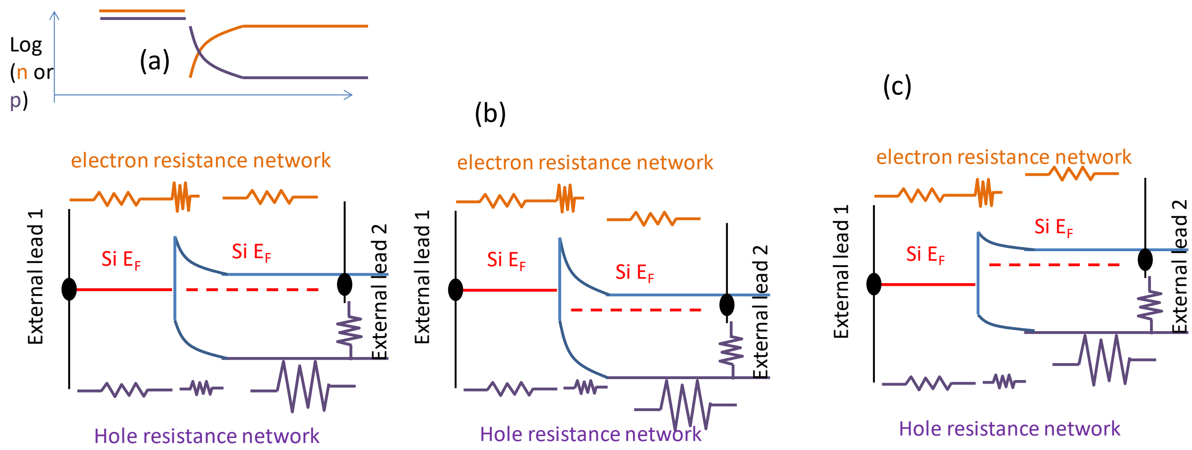


Figure 2 (a) Equilibrium band diagram and the carrier concentration, which translated to and equivalent resistance network. The band diagram and resistance network for (b) reverse bias (c) forward bias

Possibility 1: All the current pass over the barrier height: Thermal Emission

There is a fixed density of states of the peak of the barrier, i.e. N_C i.e. conduction band density of states of the semiconductor. As a reminder, the $E(k)$ diagram is used to generate band diagram $E(x)$ where the density of states at the band edges are N_C and N_V for conduction and valence band respectively. These are filled by probability, which depends upon the fermi level energy. Note that in the $E(k)$ diagram all energies are considered with states k_x shown vs energy. In comparison, in band diagram, the energy dependence of states is compressed to an equivalent N_C states only at the band edge i.e. E_C. (see Figure 3(b))

(see Taur and Ning Chapter 2.1 for detailed study)

From the $E(k)$ diagram, left half these states ($k_x < 0$) have an effective velocity to the left and other half ($k_x > 0$) has a velocity to the right. The net velocity is zero if occupied state in the left and right are equal. Equivalently in the band diagram, given a fixed N_C at E_C, half travel left and other half travel right.

We will assume that states traveling from left to right at the peak barrier is supplied only by the contact on the left and vice versa.

This makes sense if you think of the peak point to be a resistor supplied by fermi levels (equivalent to voltage sources) from left and right. The current from left to right ($J_{L\to R}$) sources on the left contact and sinks on the right contact and vice versa. The net current (J=$J_{L\to R} - J_{R\to L}$).

An incorrect analogy. If a resistor has two voltage sources V_{Left} and V_{Right}, then we say $J_{L\to R}$ depends on V_{Left} only assume $V_{Right} = 0$ and vice verso. Then, we calculate net current $J = R(V_{Left} - V_{Right})$. This is valid for linear resistors and hence invalid here.

Instead, in our case, we calculate $J_{L\to R}$ given E_{F-Left} and $E_{F-Right}$ and not E_{F-Left} with $E_{F-right} = 0$; Then, we subtract the current. The assumption is for right moving current – left electrode is a source and right electrode is sink such that any current that can cross the barrier will be absorbed 100% by the right electrode sink. So we need to calculate only what electron density can cross from left to right i.e.

$J_{L\to R}$ and vice versa separately and then calculate the net J. **Essentially, $\boldsymbol{J_{L\to R}}$ and $\boldsymbol{J_{R\to L}}$ do not interact** and hence the net current can be calculated by the simple subtraction.

Calculating $\boldsymbol{J_{S\to M}}$ and $\boldsymbol{J_{M\to S}}$

1. Looking from the semiconductor to the metal, the barrier height (semiconductor Fermi level to peak barrier) is modulated from the semiconductor to metal side by $V_{bi} - V_{app}$. So it increases and decreases with bias. The electron density at the barrier point that is able to move from semiconductor to metal is given by

$$J_{S\to M} = qvN_c \exp(-\frac{V_{bi} - V_{app}}{V_T})$$

Where v is velocity of electrons at that energy (otherwise approximated as thermal velocity). In any case, the velocity relatively weakly V_{app} dependent, compared to the $n(V_{app}) = n_{no} \exp(-\frac{V_{bi}-V_{app}}{V_T})$

2. Looking from the metal to the semiconductor, the barrier height (Metal Fermi level to peak barrier). The barrier height from the metal to semiconductor side remains constant at $\phi_B = V_{bi}$ independent of bias.

$$J_{M\to S} = qvN_c \exp(-\frac{V_{bi}}{V_T})$$

Thus net current

$$J = J_{S\to M} - J_{M\to S} \; = \; qvN_c \exp\left(-\frac{V_{bi}}{V_T}\right)\left(\exp\left(\frac{V_{app}}{V_T}\right) - 1\right) = I_o\left(\exp\left(\frac{V_{app}}{V_T}\right) - 1\right)$$

This is an <u>ideal</u> diode or rectifier current. The accurate current calculation gives the following equation

$$J = AT^2 \exp -\frac{V_{Bi}}{V_T}(\exp\left(\frac{V_{app}}{V_T}\right) - 1)$$

Where $qv_R N_C = AT^2$, where A is Richardson's constant and v_R is Richardson's velocity. See. https://ecee.colorado.edu/~bart/book/book/chapter3/ch3_4.htm for a proof of this statement.

Current for small voltage $V_{app} \ll V_T$, observe the **<u>linear regime.</u>**

$$J \approx AT^2 \exp(-\frac{V_{bi}}{V_T})\frac{V_{app}}{V_T}$$

Contact resistance for small $V_{app} \ll V_T$;

$$\frac{dJ}{dV_{app}} = \; AT^2 \exp(-\frac{V_{Bi}}{V_T})\frac{1}{V_T}$$

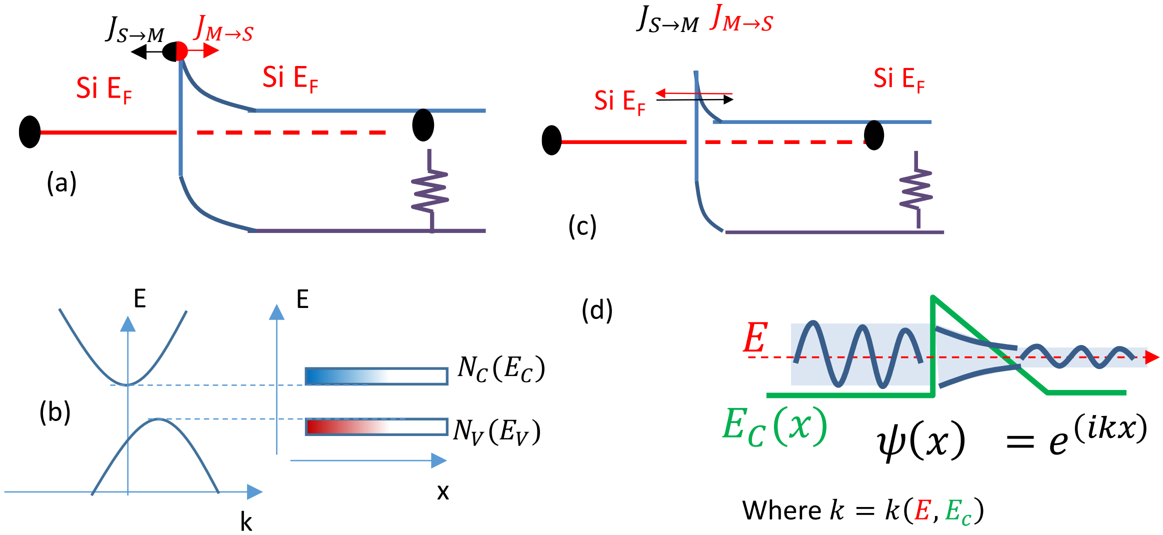


Figure 3 (a) Band diagram at low doping where over the barrier current is dominant; (b) the E(k) diagram is modified to E(x) diagram where conduction band has density of state N_C at E_C and similarly valence band has N_V at E_V; (c) At high doping where the current is primarily by tunneling (d) Tunneling calculation based on finding transmission through the barrier which depends on a decay of the amplitude in the barrier.

Possibility 2: All the current passes under the barrier height by tunneling: Field Emission

This situation will occur when the barrier is transparent i.e. the barrier width is thin. Here as well, the current computation is limited to the barrier region. The rest of the device is essentially not blocking the current significantly and thus QFL is flat here. The QFL difference appears across the barrier where tunneling current is calculated. We will discuss the exact method here as we will discuss tunneling later. However, this does not invalidate our approach even though the mechanism of current transport in the region of interest has changed. However, the region of interest itself has not changed (which was determined by QFL analysis).

Also, the valence band contribution still remains insignificant. You can try to see if any of the previous arguments have changed.

Tunneling Transport

Tunneling is described in detail in a different document.

In a very simplistic description, essentially,

$$J_{L\to R} = qnv = qN_C v_R T(E_{FL})$$

where v is the velocity with which n electrons impinge on the barrier (where $nv = N_C v_R$ are shown in the previous section)- *we do not care about the exact details of this nv factor as it does not affect the dependence of current with V or T strongly*. T is the probability of tunneling i.e. out of v times a electron impinges per second, only a fraction T attempts are successful thus producing a current. Hence vT is like an "effective" velocity term. *This T factor is the most important as it contains the major V dependence.*

So how do we evaluate T?

We know that outside of the barrier, the wave function $\psi(x)$is a plane wave.

$\psi(x) = \exp ikx$, where $k(x) = \frac{\sqrt{2m(E-E_c(x))}}{\hbar}$

Thus, the probability of transmission anywhere outside the barrier is unity. Hence, this waveform just travels without decay.

$$T = |\psi(x)|^2 = 1$$

Inside the barrier, $E < E_c$, hence $k \in Imaginary$.

Hence, $\psi(x) = \exp(-kx)$ i.e. it is a decaying function. The probability of transmission through the barrier for a case where $k(x) = k$ i.e. independent of x and constant

$$T = |\psi(x)|^2 = \exp -2kx$$

If $k(x)$ varies with x, then we get an integral

$$T = \exp(-2\int k(x)dx)$$

Where $k = k(E, E_c(x))$ and integral limits are from the entry to exit of the electron in the barrier.

Finally, for a ***triangular barrier approximation*** of the depletion region (which is actually parabolic) as leads to an analytical solution, $E_C(x) - E = (E_{peak} - E) - Fx$; where F is the effective electric field. When the barrier starts at $x = 0$ i.e. $E_C(x) - E = (E_{peak} - E)$ and ends when $E_C(x) - E = 0$ i.e. there is no barrier.

Hence the integral $\int k(x)dx = \int \frac{\sqrt{2m(E-E_c(x))}}{\hbar} dx = \frac{2}{3}\frac{\sqrt{2m}}{\hbar F}\left(E - E_c(x)\right)^{\frac{3}{2}}$

$= \frac{2}{3}\frac{\sqrt{2m}}{\hbar F}\left(E_{peak} - E\right)^{\frac{3}{2}}$ using the limits

$$T = \exp(-2\frac{2}{3}\frac{\sqrt{2m}}{\hbar F}\left(E_{peak} - E\right)^{\frac{3}{2}})$$

If E is the energy at the edge of the conduction band, then $E_{peak} - E = \phi_B$

$$T = \exp(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}})$$

$$J_{L\to R} = qnv = qN_C v_R T(E_{FL})$$

The net current $J = J_{L\to R} - J_{R\to L} \approx J_{L\to R}$ when $J_{L\to R} \gg J_{R\to L}$ i.e. at large applied bias.

$$J = qN_C v_R \exp(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}})$$

At small bias, it will be interesting to develop an approximation

The field is given approximately by $F \approx \frac{V_{bi}-V_{app}}{d_{depletion}}$ which is same for both terms $L \to R$ and $R \to L$

The barrier looking from left to right is $\phi_{BL\to R} = \phi_o = qV_{bi}$

The barrier looking from right to left is $\phi_{BR\to L} = \phi_o - qV_{app} = qV_{bi} - qV_{app}$

$$J = J_{L\to R} - J_{R\to L} = qN_C v_R [T(V_{bi}) - T(V_{bi} - V_{app})]$$

$$J = qN_C v_R \left\{ \exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}}\right) - \exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B - qV_{app})^{\frac{3}{2}}\right)\right\}$$

Assuming $V_{app} \ll V_{bi}$,

1. we can expand $(1+x)^{3/2} = 1 + \frac{3}{2}x + \cdots$

$$J \approx qN_C v_R \exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}}\right)\{1 - \exp\left(+\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}\,(\frac{3}{2}qV_{app}\sqrt{\phi_B})\right)\}$$

2. Further, expand exponential (assume $+\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}\left(\frac{3}{2}qV_{app}\sqrt{\phi_B}\right) \to 0$) i.e. F is high

$$J \approx qN_C v_R \exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}}\right)\{\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}\,(\frac{3}{2}qV_{app}\sqrt{\phi_B})\}$$

Thus, the resistance at low bias, $\frac{dJ}{dV_{app}} = qN_C v_R \exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}}\right)\left\{\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}\left(\frac{3}{2}\sqrt{\phi_B}\right)\right\}$

This is a strong function of electric field F.

Extreme tunneling in MS contact to make ohmic contacts

When F becomes high, the exponential term (red) can become very high i.e. the barrier becomes more transparent. This will produce a very high current. $F \propto N_A$; Hence increasing doping can making highly ohmic contact. The ohmic nature (resistance which is negligible compared to the device) is not due to small barrier but a very transparent barrier due to tunneling.

https://people.eecs.berkeley.edu/~hu/Chenming-Hu_ch4.pdf

Observed difference between pn junction, pure tunneling (Field Emission) vs Thermal emission

In forward bias, cut-in voltage depends upon V_{bi} for thermal emission. For pn junction, this depends upon doping (~0.7V). This can be $E_g/2$ to E_g. Below $V_{bi} = E_g/2$, the pn junction is low doped. Q: What would be the doping? Is it possible given mimimum unintentional doping in Si is $10^{16}/cc$.

For MS contact, this depends upon ϕ_B, which is a materials / interface property of the metal and semiconductor. ϕ_B can range from 0 toE_g.

In reverse bias, thermal emission is constant with bias, $I = I_o\left(\exp\frac{V_{app}}{V_T} - 1\right) \approx I_o$ when $exp(\frac{V_{app}}{V_T}) \ll -1$;

However, for Field emission, the current is bias or field dependent

$$J = qN_C v_R \exp(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar F}(\phi_B)^{\frac{3}{2}})$$

Increasing the reverse bias current is the big deal for making low resistance contacts as in forward bias the current is high after cut-in but in reserve bias the current never increases for ideal diode i.e. $I \approx I_o$. However tunneling provides an alternative to increase reverse bias leakage significantly with electric field.

In extreme cases, the barrier can become completely “transparent” and does not block any current compared to the rest of the device (say the pn junction); Hence it behaves like the contact is ideal – see Figure 4(c-d)

Q: Can we ensure that the Schottky barrier IV dominated? Easy question: What is the principle to use? Next Stage: How can we engineer it?

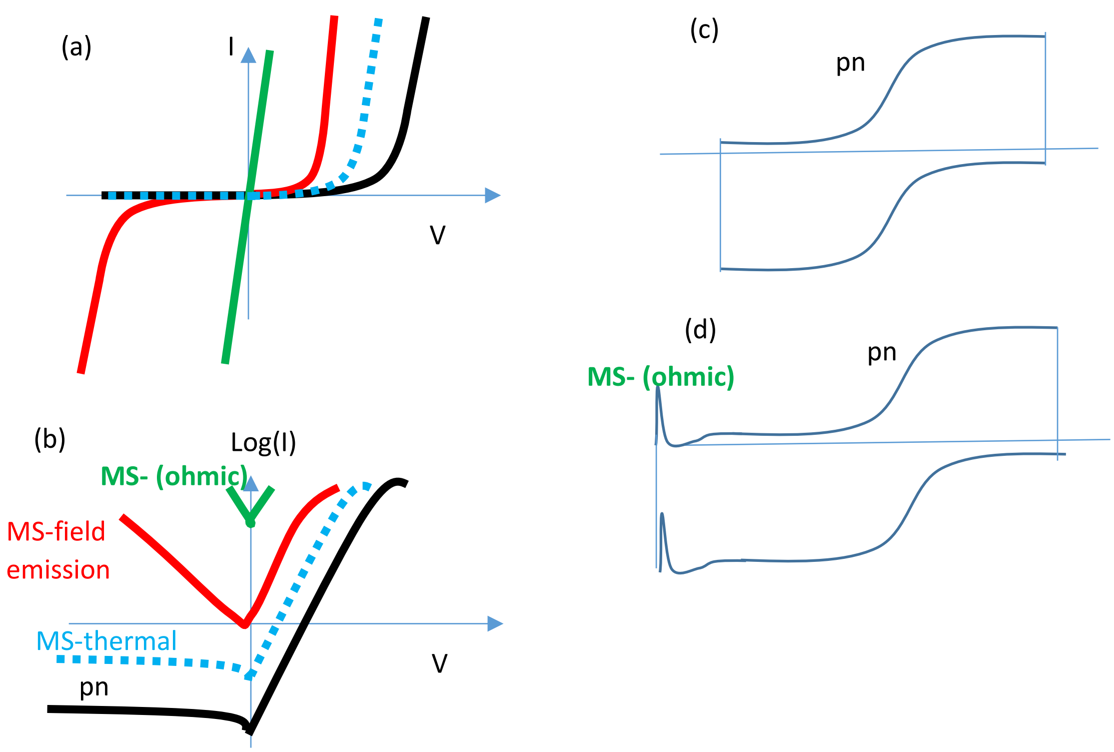


Figure 4(a) I(V) for pn diode(black), schottky diode with thermal emission (blue), field emission (red) and strong field emission leading to almost ohmic behavior (green). Note two observations.(i) Schottky barrier cut-in voltage in forward bias in smaller than pn junction and depends upon ϕ_B. This provides a simple way to measure Metal Semiconductor band alignment. (ii) Reverse bias leakage for thermal current is constant. As field emission increases, the current becomes voltage dependent to allow higher current for increased reverse bias. (c) ideal pn junction – contacts are assumed ideal i.e. does not block current (d) pn-junction with metal contact that are ohmic i.e. effectively negligible resistance compared to pn junction. Note the thin *tunneling barrier. Also not that doping near the contact is increased to reduce depletion width and hence tunneling barrier width.*

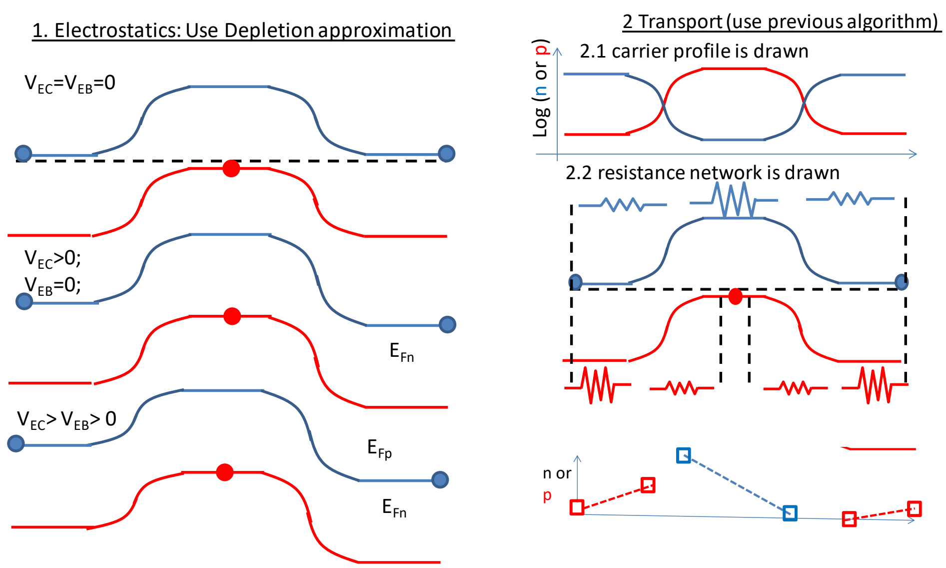
Possibility 3: As the barrier has non-uniform height,

A case between pure tunneling (field emission) and thermal emission is possible. It just complicates the formula because of mixing of two mechanisms. We will not study this here but it is a simple extension.

Bipolar Junction Transistor

This is now a 3 terminal device which is different from the previous 2 terminal devices. So how do we solve for current? Let us apply the same principles and methods as before and see how far we go.

Step 1 (Electrostatics): Draw Equilibrium band diagram. Find out where voltage will drop i.e. band diagram in $V_{EC} > 0$ and $V_{EB} > 0$.



Step 2: (QFL Analysis): Draw n(x) and p(x) assuming equilibrium. Assess where electron and hole QFL is flat. Unlike earlier, there is a p-region contact in the middle of the device. Here we need to judge whether it contact conduction or valence band. Given the p-region needs a contact, a p-metal is preferred to make an ohmic contact. So while the valence band has a good connection with base contact, the conduction band current cannot (easily) flow into the base contact.

For electron, the p-region is where QFL drops. Elsewhere E_{Fn} is flat. For holes, both emitter and collector quasi-neutral regions are parallel connections for hole current. Elsewhere E_{Fp} is flat. Emitter hole current should dominate as the junction is in forward bias while CB junction is reverse biased.

Step 3 (detailed diffusion calculations): The diffusion currents needs to be calculated where QFL bends for electrons and holes.

$J_n = qDn_{po}(\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(-\frac{V_{CB}}{V_T}\right))/L_B$ where L_B is the quasi neutral region length of the base (i.e. base length minus depletion from both junctions)

$J_n \approx qDn_{po}(\exp\left(\frac{V_{BE}}{V_T}\right))$ where $V_{CB} \gg V_{BE}$ Saturation regime

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$$J_n = qD\frac{n_{po}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(-\frac{V_{CE} - V_{BE}}{V_T}\right)\right)}{L_B}$$

$$J_n \approx qDn_{po}\exp\left(\frac{V_{BE}}{V_T}\right)V_{CE}/V_T\ /L_B = q\mu n_{po}\exp\left(\frac{V_{BE}}{V_T}\right)V_{CE}\ /L_B$$

When $V_{CE} \ll V_T$ (Linear Regime)

$$J_n = \frac{qDn_{po}}{L_B}\left(\exp\left(\frac{V_{BE}}{V_T}\right)\right)$$

When $V_{CE} \gg V_{BE} \gg V_T$ (Saturation)

$$J_n = \frac{qDn_{po}}{L_B - \Delta L_B(V_{BC})}\left(\exp\left(\frac{V_{BE}}{V_T}\right)\right)$$

Base length modulation due to drain depletion length due to reverse bias V_{BC} increase reduces base width $\Delta L_p(V_{BC})$

$$\Delta L_p(V_{BC})$$

Q: Why does it produce an approximately linear $I_C V_{CE}$ after saturation?

Hint: Calculate L_B change with V_{CE} for fixed V_{BE} and then this will be quadratic. It can be linearized by Taylor series under reasonable assumptions.

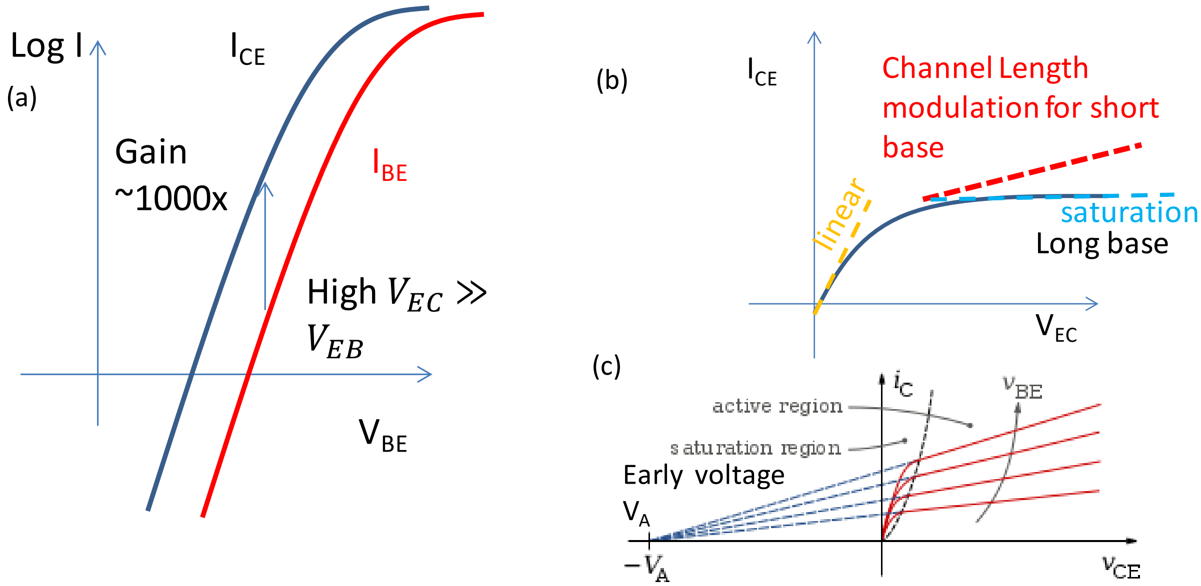

Figure 5(a) I vs V_{BE} shows gain for high $V_{CE} \gg V_{BE}$ which is constant for a significant V_{BE} but reduces at high V_{BE} when series resistance kills the exponential dependence of I_C s(b) Linear (at low V_{EC}) vs. saturation regime where saturation regime has channel length modulation for short base (c) channel length modulation leads to early voltage.

Step 4: We can now draw the QFL in the regions of transport i.e. where QFL in not flat.

The hole currents can be calculated due to forward biased emitter-base junction (J_{pE}) and reverse biased collector-base junction (J_{pC})

$$J_p = J_{pE} + J_{pC} = \frac{qDp_{no}}{L_E}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right) + \frac{qDp_{no}}{L_c}\left(\exp\left(-\frac{V_{CE}-V_{BE}}{V_T}\right) - 1\right) \approx \frac{qDp_{no}}{L_E}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right)$$

When V_{BE} is significantly forward biased.

Gain

Gain (β) is defined output (collector) current ratio to input (base) current for a common emitter configuration as shown in Figure 5(a).

$$\beta = \frac{J_C}{J_B}$$

$$J_B \ll J_E \approx J_C$$

Under saturation

$$J_n \approx \frac{qD_n n_{po}}{L_p} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$J_p \approx \frac{qDp_{no}}{L_E}\left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right)$$

$$\beta = \frac{J_E}{J_B} = \frac{\frac{qD_n n_{po}}{L_p}}{\frac{qD_p p_{no}}{L_E}} = \frac{D_n}{D_p}\frac{L_E}{L_p}\frac{N_{D-E}}{N_{A-B}}$$

Back-to-back diode vs BJT

The back-to-back diode is compared to BJT to show how the conduction band circuit is significantly different (Figure 6). In BJT, the electrons never directly encounter the base electrode and have a direct path from emitter to collector. However in back to back diode, such a direct path is "broken" by the base terminal. Electrons have to, thus, transfer out of the conduction band to the contact in the base.

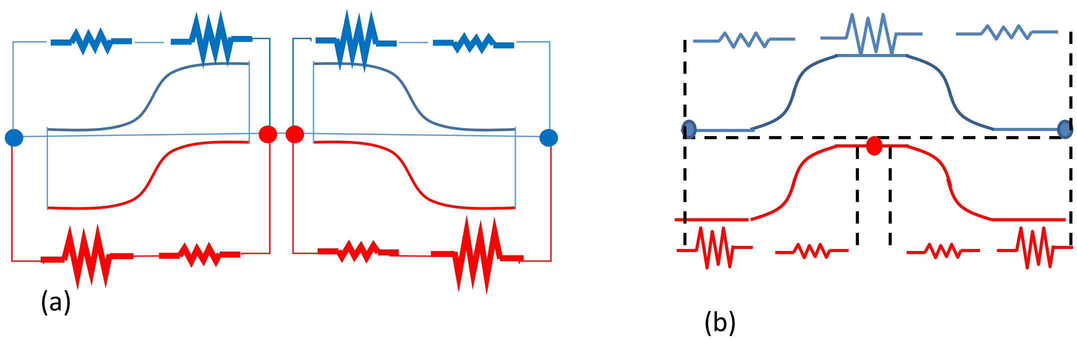

Figure 6(a) Back-to-back diodes are independent compared to (b) a BJT. This does not change the valence resistance network but the conduction band network is changed. The back-to-back diodes do not have a direct path from emitter to collector. All electrons will "see" the base terminal while in BJT the electrons never encounter the base terminal (assuming no Recombination Generation).

Why does the base contact not affect electrons directly but is strongly coupled to holes?

A 2D view of the BJT provides more insight (Figure 7). There are two independent resistor networks or channels (hole and electrons).

1. For hole circuit, the base is a short and collector and emitter are open (or high resistance). Hence the base voltage and E_{Fp} is same as base terminal (E_{FB}).

The change of E_{Fp} to emitter (E_{FE}) and collecter (E_{FC}) occurs elsewhere i.e. in the quasi neutral region of the emitter and collector.

This electrostatic potential is applied through the valence band by the highly conductive hole channel or network in the base. This coupling of entire base holes to base terminal is strong.

2. For electron circuit, the situation is reversed. The base on highly resistive while emitter and collector are conductive.

   There electrons emitted from the emitter have two choice of destination or sinks (i) base terminal (ii) collector. The selection of destination depends upon shortest path. When the base is close then the electrons travel to the base. However, for substantial electrons, the base is far away compared to the collector. Hence these electrons largely prefer the collector sink. This is purely a geometric argument.

If the geometry changes i.e. the base is very wide compare the depth, then most electrons will prefer the base terminal as the sink.
If the base width is narrow, then most electrons will prefer the collector as the sink.

This way, by making a narrow base width in the 2D network shown in Figure 7 (a-b), the base can be do-coupled from the electron network significantly – which is equivalent to the 1D network in Figure 6 (b).

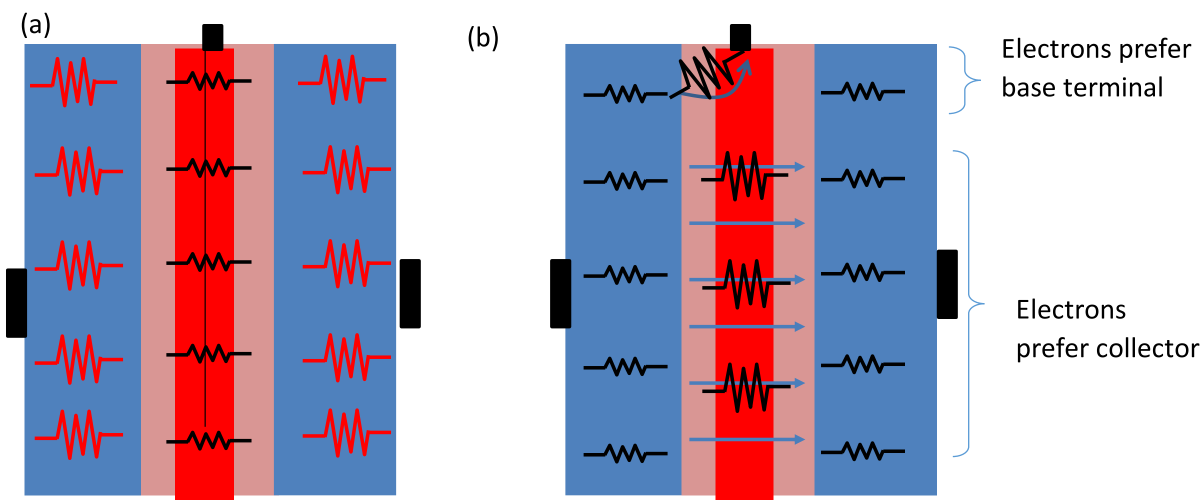

Figure 7 2D BJT cross section that shows the npn regions with connections to terminals on the periphery or surface. (a) Hole circuit which resembles 2 diodes (b) electron circuit where electrons emitted from emitter have 2 choices of sink (i) base terminal and (ii) collector and the choice is determined by geometric considerations of least distance to the sink. A the top, the base is preferred but the most of the lower parts the collector is preferred. Thus, this way the electron circuit with a narrow base has a negligible connection to the base terminal and substantial connection to the collector terminal, which is equivalent to the 1D circuit shown earlier.

Summary

The QFL analysis provides simplification of the transport problem by identifying the critical zones controlling (blocking) current. Rest of the device need not be considered further. A detailed calculation of current is needed where current is blocked i.e. E_{Fn} or E_{Fp} are not flat. While this was developed for drift diffusion devices, it can be useful for other types of transport like over the barrier (thermal emission) and tunneling (field emission) as given in MS contact example. Though developed for 2 terminal devices, it can be extended to multi-terminal device e.g. BJT etc.

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