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CHAPTER 4

THE JUNCTION TRANSISTOR

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CHAPTER 4

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THE JUNCTION TRANSISTOR

Abstract - The operation of the junction transistor is explained in detail considering the junction barrier, minority carrier injection, space charge neutralization and diffusion phenomenon. Furthermore, the physical and electrical parameters affecting transistor performance are given considerable attention. The inherent temperature sensitivities of the transistor are pointed out, and the factors contributing to a general deterioration of performance at high frequencies are analyzed. Modifications of the basic transistor that will greatly extend the maximum operating frequency are described. Finally, transistors that exhibit thyratron-like characteristics are discussed along with other single and multiple junction devices intended for special applications.

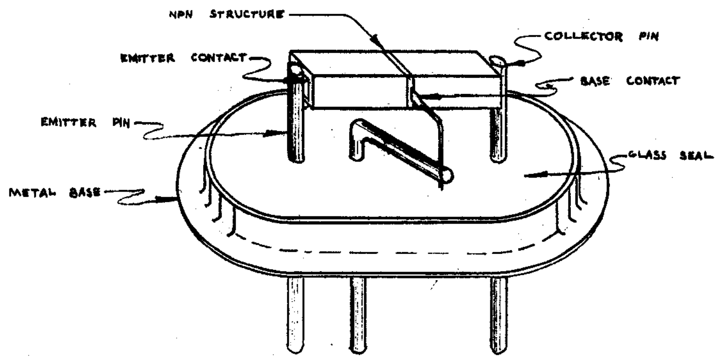


Figure 4.1. Construction of a Grown Junction Transistor.

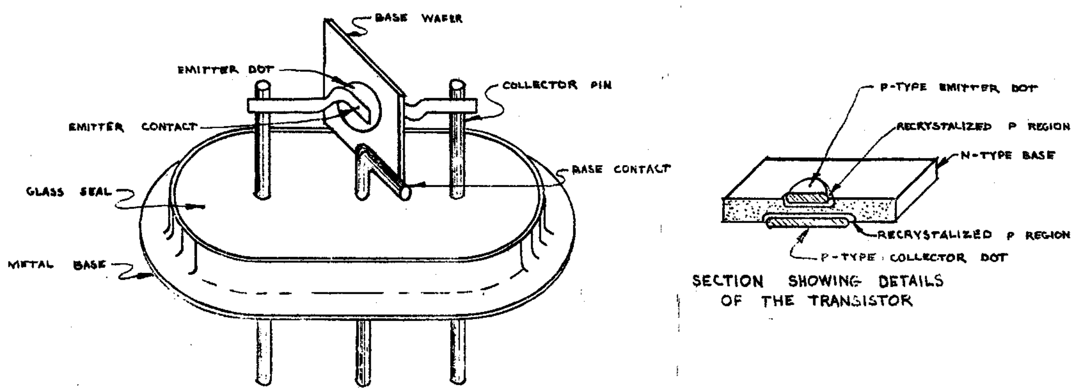


Figure 4.2. Construction of an Alloy Junction Transistor.

INTRODUCTION

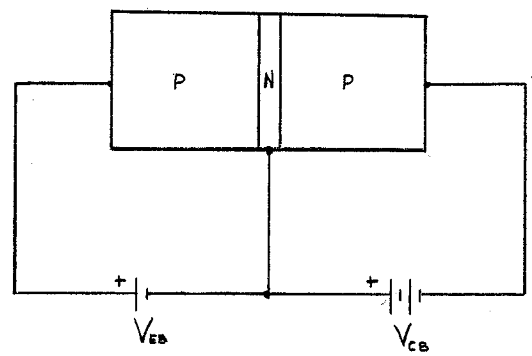
In chapter 1 an elementary description of the junction transistor was given. The NPN and PNP structure of the transistor was shown, and the paths of the current carriers were illustrated. Here the potential barriers existing at the junctions will be taken into consideration, and the mechanisms responsible for the transport of current carriers across the base will be looked into more closely. Furthermore, the design factors affecting performance (current gain, linearity, maximum ratings, temperature sensitivity, and frequency response) will be discussed. Finally, special designs used to improve characteristics for particular applications will be covered. This latter category will include the drift, tetrode, field effect, hook, and unijunction transistors.

THE JUNCTION TRANSISTOR

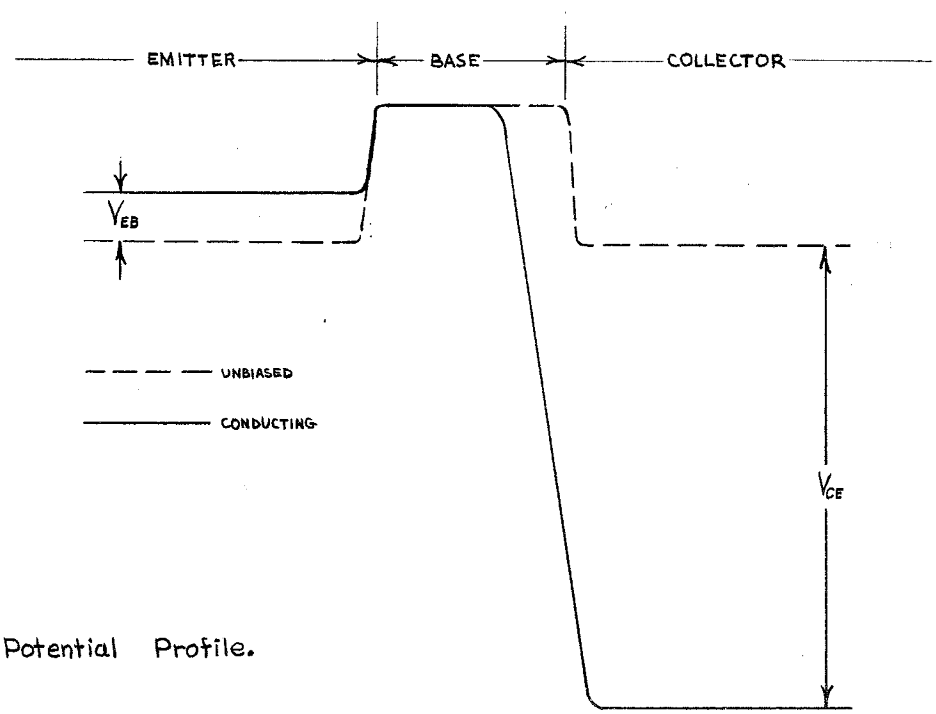
Two possible configurations used in the fabrication of junction transistors are illustrated in figures 4.1 and 4.2. These will be discussed briefly so that the nature of the device can be appreciated. However, a more detailed description of manufacturing techniques will be given in the next chapter.

Figure 4.1 illustrates a grown junction transistor. A NPN transistor of this type is made by dipping a seed crystal into molten germanium which has been moderately doped with a N-type impurity. The seed is withdrawn slowly from the melt; and the doped germanium crystalized on the seed, producing a N-type crystal. After the crystal has grown for some time, sufficient P-type impurity is added to the melt to overcome the N-type impurity; and a thin P-type layer having a high resistivity is grown. Finally, an excess of N-type impurity is dumped into the melt, again reversing the impurity type, so a low resistivity N-type portion is grown. This procedure gives the required NPN structure. Using this technique, good quality transistors having base widths in the order of 0.001 inch can be made.

An alloy junction transistor is shown in figure 4.2. To fabricate this type of transistor, two dots of a P-type impurity having a low melting point are placed on opposite sides of a thin N-type germanium wafer which has a high resistivity. This assembly is then heated, melting the dots which take some of the germanium into solution. When the assembly is cooled, the dissolved germanium, which is now heavily doped with the P-type impurity, recrystalizes on the wafer around the dots. This procedure yields two heavily doped P-type regions separated by a thin layer of lightly doped N-type material. In practice, the penetration of the dots into the wafer can be controled to produce base widths of 0.001-0.003 inch.



a. Biasing Arrangement.



b. Potential Profile.

Figure 4.3. Variation of Potential with Distance through the Base Region for Both an Unbiased and a Conducting Transistor.

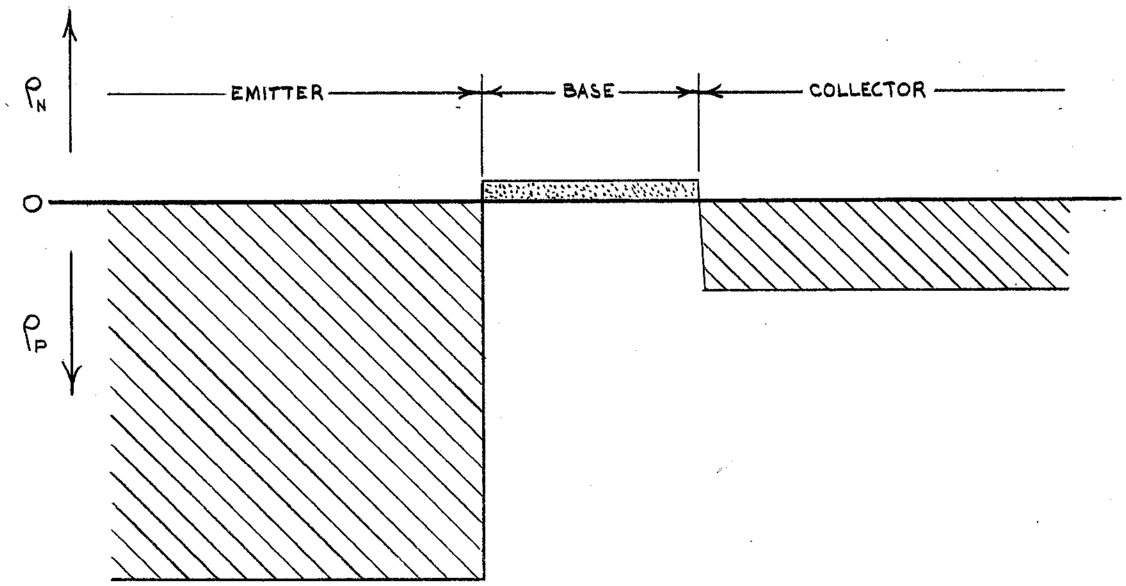
Barrier Formation. As with a junction diode, when the PN junctions of a transistor are formed, there is an initial diffusion of current carriers across the junction, which produces a charge unbalance. This charge unbalance gives rise to a barrier potential and its associated barrier field that is confined to a narrow depletion region. This barrier opposes further diffusion and establishes an equilibrium condition. Therefore, in an unbiased transistor, barriers will be formed at the emitter and collector junctions producing the potential profile shown in figure 4.3b (dashed line).

Transistor Operation. When a reverse bias is applied to the collector junction as shown in figure 4.3a, the barrier height at the collector junction is increased by an amount equal to the applied voltage. The entire collector voltage is dropped across the depletion region of the collector junction, so there is no electric field acting on the current carriers in the base and in the collector. Therefore, no current will flow across the collector junction, except for a small saturation current caused by the diffusion of thermally generated minority carriers to the junction.

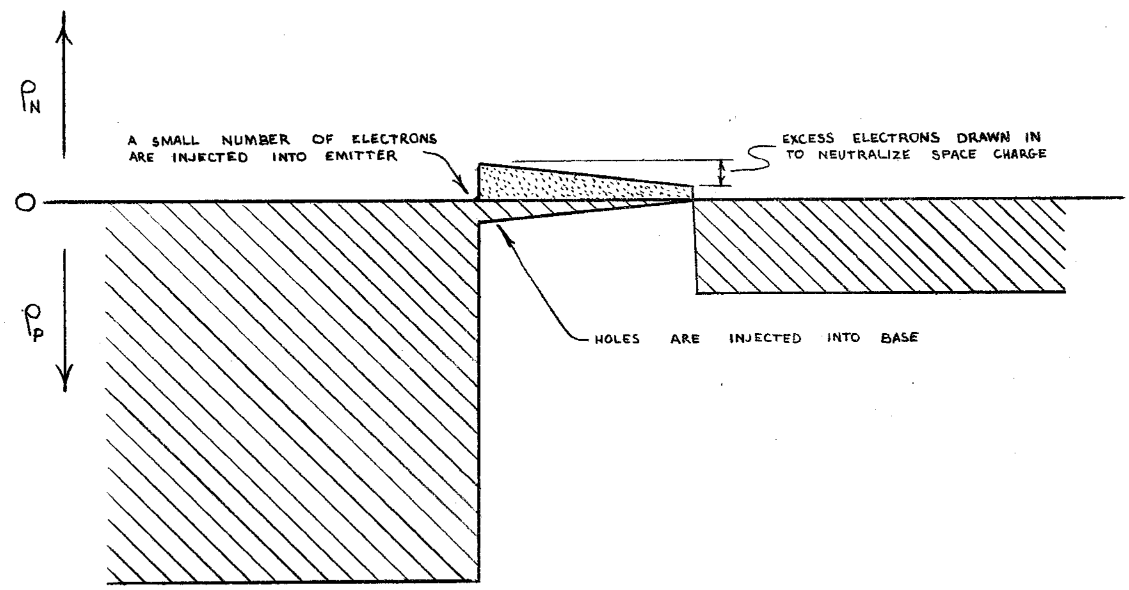
If now a small forward bias is applied to the emitter junction, this barrier will be lowered, permitting the diffusion of holes into the base. It should be emphasized that the holes are not accelerated into the base by the forward bias, but instead the barrier is lowered permitting the thermal diffusion of holes through a reduced barrier field. Furthermore, after the holes are injected into the base, they are not acted upon by an electric field but continue to diffuse until they reach the collector junction. When the holes arrive at the collector junction, they enter the barrier field which sweeps them across the junction into the collector (the drift forces of the electric field are considerably stronger than the diffusion forces).

Space Charge Neutralization. When the emitter junction is forward biased, holes are injected into the base. These excess positive charges create an electric field in the base region. However, the mobile electrons in the base are acted upon by this field and are attracted to the positive charges. Electrons are then drawn in from the base terminal to neutralize the electric unbalance created by the injected holes. This process, which has already been explained in chapter 2, is called space charge neutralization. The hole and electron densities are plotted in figure 4.4 as a function of distance in the vicinity of the base to illustrate this phenomenon.

One result of space charge neutralization is the elinination of the repulsive forces acting on the injected holes. Therefore, the holes do not diffuse through the base by mutual repulsion, instead they are transported across the base by thermal diffusion supported by the higher concentration of holes near the injection source (emitter junction).



a. Nonconducting Transistor.



b. Conducting Transistor.

Figure 4.4. Plot of the Hole (ρ_P) and Electron (ρ_N) Densities with Distance through the Base for a PNP Transistor in Both the Conducting and Nonconducting States.

Current Gain. Before going further into the operation of the transistor, two parameters need to be defined: the common base current gain (α_B) and the common emitter current gain (α_E). The common base d.c. current gain is defined as the ratio of the collector current to the emitter current (figure 4.5a). It has been shown that the collector current will be less than but very nearly equal to the emitter current for a junction transistor so α_B will approach unity. In practice, values of α_B ranging from 0.900-0.995 are common.

The common emitter d.c. current gain is defined as the ratio of the collector current to the base current (figure 4.5b). Since the base current is small in comparison to the collector current, α_E will be considerably greater than one. Values of α_E corresponding to those given for α_B range from 10-200. (Note: the common emitter current gain is sometimes given as the beta (β) current gain.)

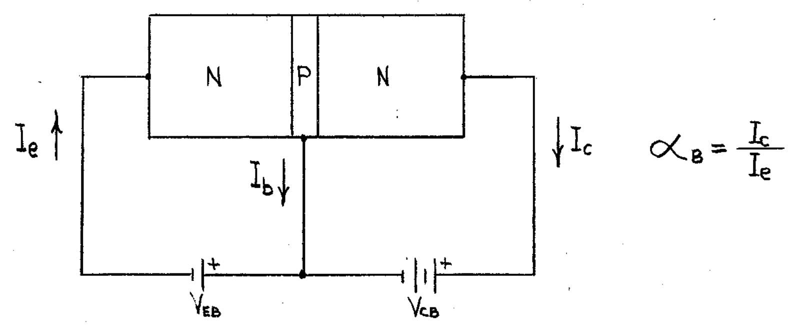
TRANSISTOR PERFORMANCE

The current gain of a transistor can be determined by considering three terms: the injection efficiency, the transport efficiency, and the collector efficiency. The physical phenomena affecting these terms will be investigated for a PNP transistor, although analagous reasoning can be applied to a NPN unit.

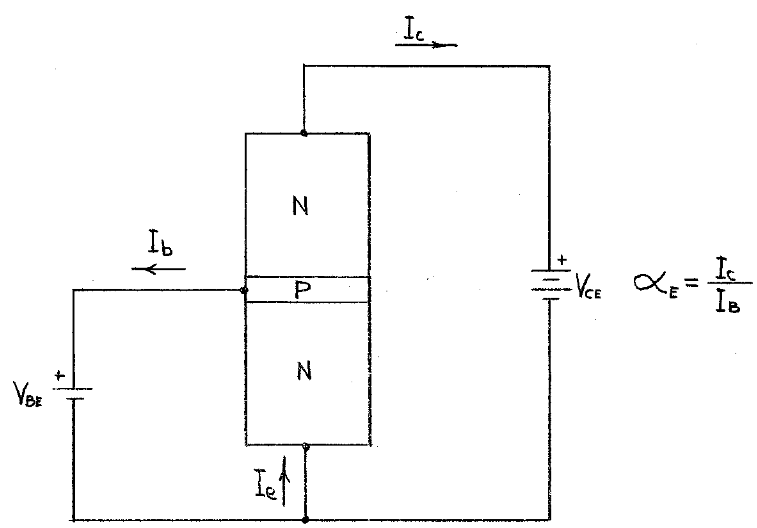
Injection Efficiency. When the emitter junction is forward biased, holes from the emitter are injected into the base; and electrons from the base are injected into the emitter. These hole and electron currents constitute the total emitter current. It is desirable to make the electron current across the emitter junction as small as possible because it produces a base and an emitter current but it does not contribute to the collector current. The electron current, then, reduces both α_B and α_E.

The injection efficiency is defined as the ratio of the hole current across the emitter junction to the total emitter current. High injection efficiencies (near unity) can be realized by suppressing the electron current across the emitter junction. One method that can be used to accomplish this is to make the emitter of a heavily doped, low resistivity material and make the base of a lightly doped, high resistivity material. Hence, when the emitter junction is forward biased, a larger number of holes will cross the junction by virtue of the fact that there is a much higher concentration of holes on the emitter side than there is electrons on the collector side.

The injection efficiency is also affected by the base width and the minority carrier lifetime in the emitter. When the emitter junction is forward biased, the hole concentration on the base side of the emitter-base junction and the electron concentration on the



a. Comon Base Circuit.



b. Comon Emitter Circuit.

Figure 4.5. Circuits Used in the Determination of the Common Base and Common Emitter Current Gain of a Transistor.

emitter side of the emitter-base junction will be determined by the resistivities of the emitter and base materials respectively and by the forward bias. However, the currents resulting from these injected carriers will be determined by the factors mentioned below.

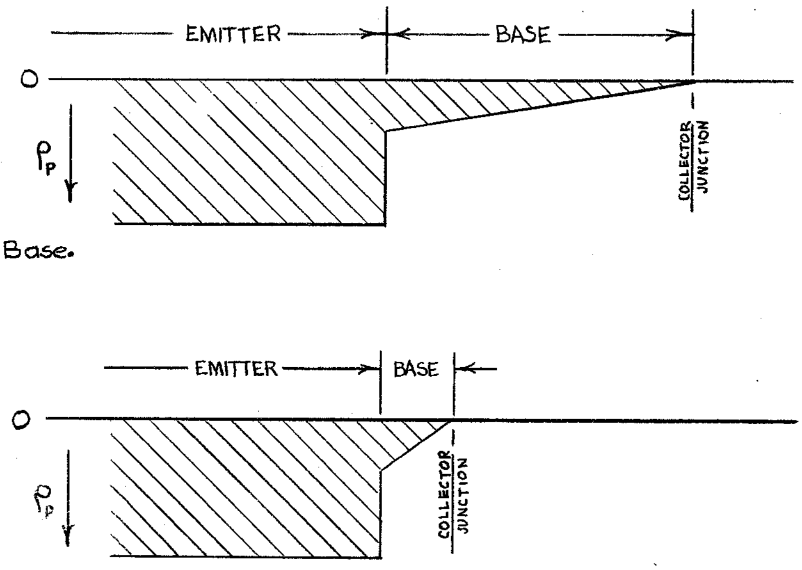
The effect of base width on the hole current across the emitter junction is illustrated in figure 4.6. Since all the holes reaching the collector junction will be swept into the collector by the reverse bias, the hole concentration at this point will be near zero; and the variation of hole concentration with distance through the base will be as shown in the figure. The diffusion current produced by these holes will be proportional to the abruptness of this variation. It should be evident from the figure, then, that the hole current through the base will be inversely proportional to the base width.

Since there is no sink for electrons in the emitter as there was for holes in the base (the collector junction), the point at which the electron concentration in the emitter reaches a neglegible value will be determined by the minority carrier lifetime in the emitter. That is, if the electrons injected into the emitter recombine rapidly, the fall off in electron concentration will be abrupt. This is illustrated in figure 4.7. Because the electron diffusion current will depend on how fast this concentration falls off, it will be strongly affected by the minority carrier lifetime. Actually, the diffusion current is inversely proportional to the diffusion length which has been defined as the average distance that a minority carrier will diffuse before recombination occurs.

To summarize, a high injection efficiency can be realized by producing a transistor which has a narrow base having a high resistivity and a low resistivity emitter with a long minority carrier lifetime. In practice, it is not too difficult to realize a hole current 1000 times as great as the electron current, which gives an injection efficiency of 0.999.

Transport Efficiency. The next term to be considered is the transport efficiency, defined as the ratio of the hole current across the collector junction to the hole current across the emitter junction. The transport efficiency will be a function of the number of holes lost in the base region by recombination. There are two significant sources of recombination: volume recombination and surface recombination.

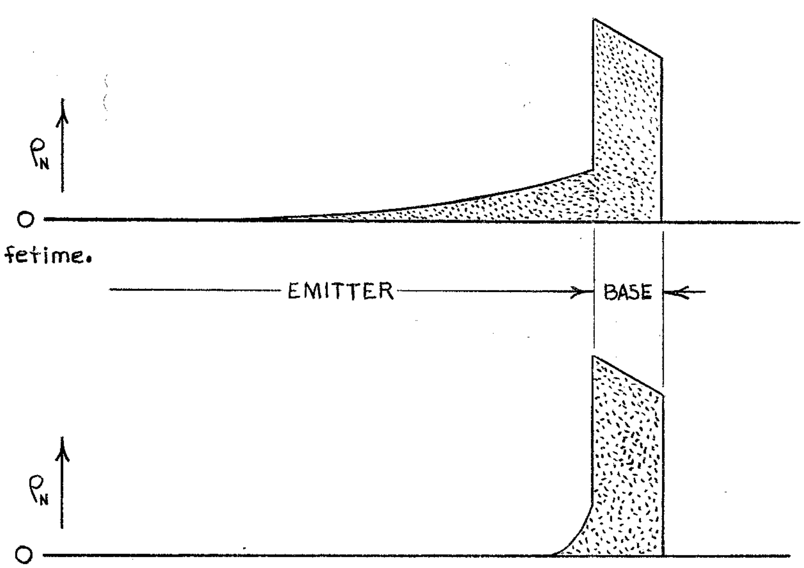
The volume recombination, which is the loss of current carriers within the body of the base region, is best described for this purpose by the diffusion length. If most of the holes crossing the emitter junction are to reach the base, the base width must be small in comparison to the diffusion length. Typical values of diffusion length are from 0.05 to 0.005 inch. Hence, with a 0.001-0.002 inch



a. Wide Base.

b. Narrow Base.

Figure 4.6. Plot of the Hole Concentration through the Base of a PNP Transistor for a Given Forward Bias, to Show the Effect of Base Width on Hole Diffusion Current.



a. Long Lifetime.

b. Short Lifetime.

Figure 4.7 Plot of Electron Concentration in the Emitter of a PNP Transistor for a Given Forward Bias, to Show the Effect of Minority Carrier Lifetime on Electron Diffusion Current.

thick base, volume recombination in the base region will be small. The number of carriers lost by volume recombination increases quite rapidly with increasing base width and with decreasing diffusion length. For a diffusion length of 0.05 inch and a base width of 0.005 inch, approximately 0.02 percent of the carriers are lost by volume recombination in traversing the base; and for a diffusion length of 0.005 inch and a base width of 0.002 inch; about 8 percent of the carriers are lost.

The second source of recombination, surface recombination, takes place when injected minority carriers diffuse to the surface of the base, become trapped, and eventually recombine. The surface recombination losses will depend on how much base-surface area is in the diffusion path of the holes crossing the base. It seems likely, then, that this term is unimportant in a grown junction transistor (figure 4.1) which has very little base-surface area. In an alloy junction transistor (figure 4.2) which has a large base-surface area, surface recombination is usually more important than volume recombination.

If the minority carriers diffusing to the surface of the base recombine slowly, the minority carrier concentration at the surface will be relatively high, inhibiting further diffusion. The rate of diffusion to the surface and, therefore, the number of carriers lost by surface recombination, will then depend on the recombination rate of the carriers trapped at the surface, or the <u>surface recombination velocity</u>. The recombination rate is determined by the condition of crystal surface: rough, contaminated surfaces give high recombination velocities while clean, etched surfaces that are free of defects give low recombination velocities.

<u>Collector Efficiency</u>. The last term used in the determination of current gain is the collector efficiency. The <u>collector efficiency</u> is defined, for a PNP transistor, as the ratio of the hole current across the collector junction to the total current across the junction. The total collector current can become greater than the hole current alone if carrier multiplication occurs within the collector junction or if a significant number of thermally generated electrons in the collector diffuse to the collector junction.

Avalanche multiplication can take place within the collector junction if the reverse bias on this junction is made sufficiently high. At high reverse voltages, it is possible for the holes crossing the junction to be accelerated enough to produce ionizations when they collide with atoms of the crystal lattice, producing additional current carriers. This can occur at reverse voltages below the breakdown voltage of the junction (self sustaining multiplication) and will produce common base current gains (α_B) greater than one. More will be said about avalanche multiplication in the discussion on reverse breakdown phenomenon.

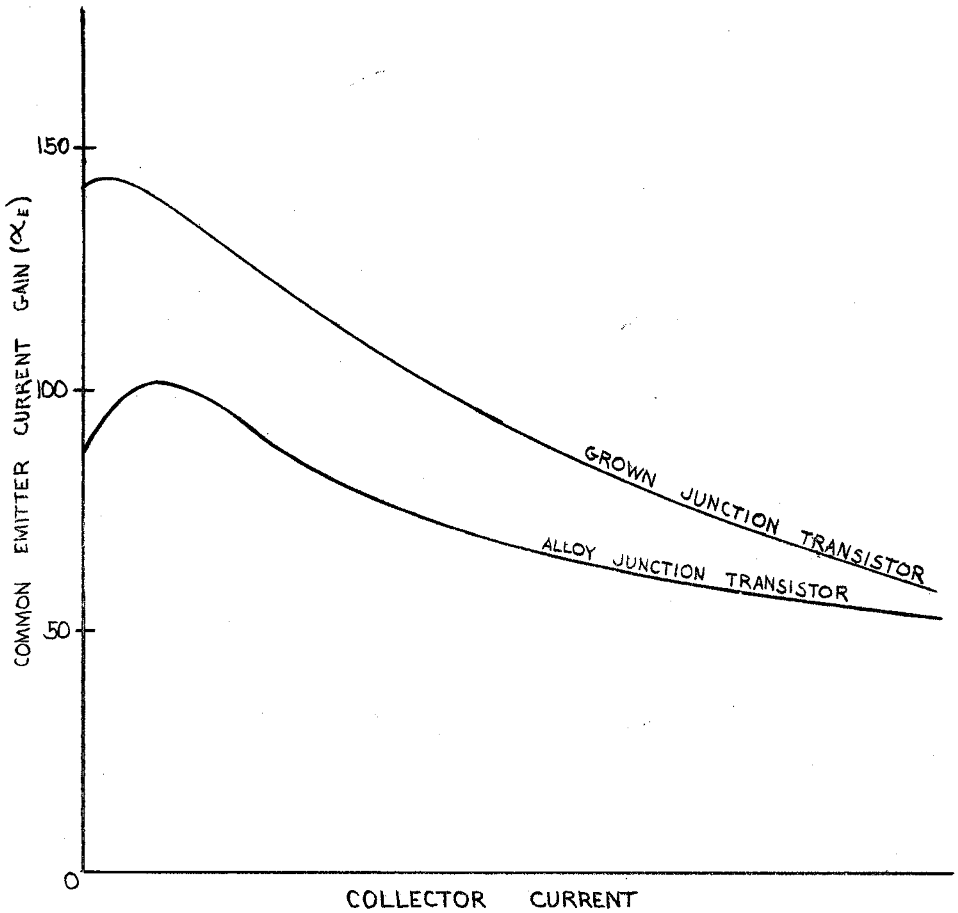


Figure 4.8. Variation of Common Emitter Current Gain with Collector Current for Grown and Alloy Junction Transistors.

Under normal circumstances, the flow of holes into the collector of a conducting PNP transistor does not affect the diffusion of thermally generated electrons to the collector junction, so the collector current is equal to the hole current across the collector junction plus the small reverse saturation current of the reverse biased junction. Therefore, the collector current is essentially equal to the hole current; and the collector efficiency is unity. However, if a high resistivity collector material is used (which means that the hole concentration is relatively low and that the thermally generated electron concentration is relatively high), the flow of holes into the collector will produce a significant increase in the hole concentration near the collector junction and will give rise to an electric field near the junction. This electric field will act on the thermally generated electrons in the collector speeding them toward the junction, thereby increasing the collector current. If the resistivity of the collector material is sufficiently high, this effect will produce an appreciable increase in collector current (over the hole current alone) and increase the collector efficiency above unity.

Improving current gain by increasing the resistivity of the collector material is generally undesirable. The reasons for this are given. First, it is possible to realize common base current gains slightly greater than one by this method. Second, if the collector current does become greater than the emitter current (α_B greater than one), the direction of the base current reverses; and the transistor becomes unstable. In this condition, the transistor is useful only in special applications which require a common base current gain considerably greater than one. And last, when a high resistivity collector is used, the current gain will increase rapidly with temperature as the number of thermally generated electrons in the collector increases. Hence, α_B will become greater than one; and the transistor will become unstable above a certain temperature.

High Current Operation. In the treatment of transistor operation, thus far, it has been assumed that the collector current was low enough that the injected minority carriers did not appreciably alter the majority carrier distribution in the base. At higher current levels the injected minority carriers will produce a significant increase in the majority carrier concentration in the base near the emitter junction because of space charge neutralization. This causes the variation in current gain with collector current illustrated in figure 4.8.

The collector current in a PNP transistor is increased by increasing the concentration of injected holes near the emitter junction. This provides a sharper variation of hole density with distance through the base and increases the diffusion current to the

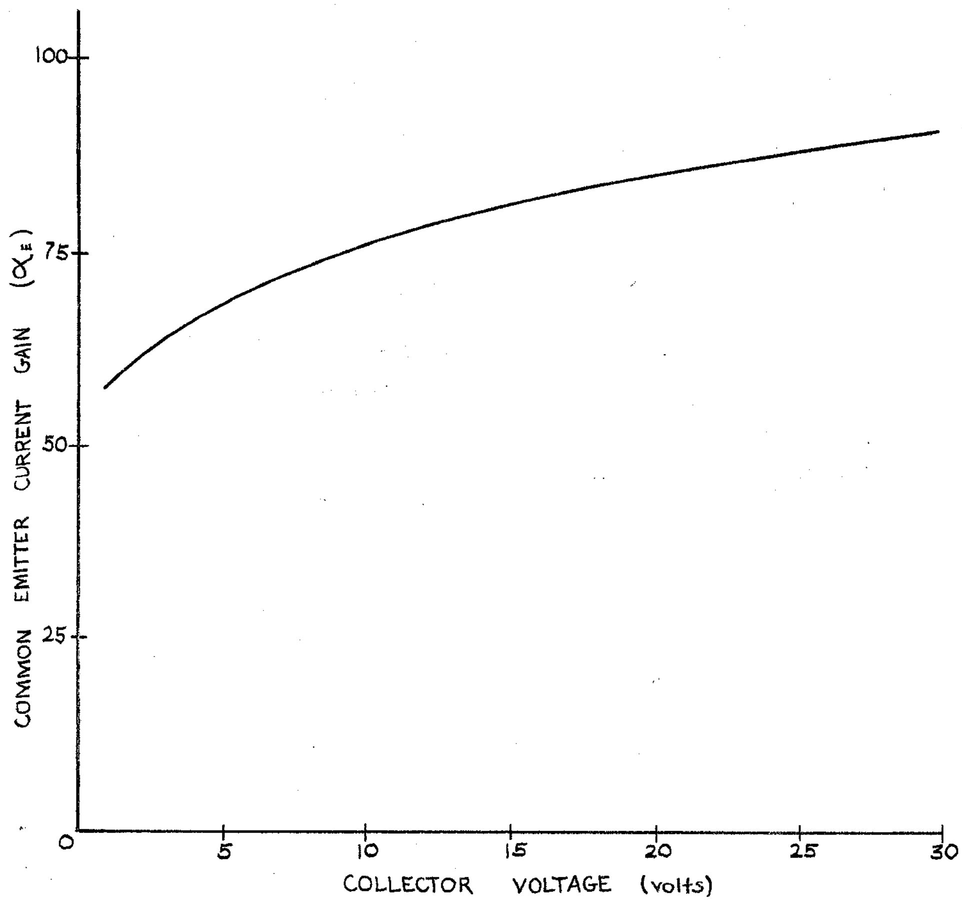


Figure 4.9. Variation of Common Emitter Current Gain with Collector Voltage.

collector junction. These injected carriers create an unbalanced charge distribution which is neutralized by excess electrons drawn in at the base terminals. Hence, the density of free electrons in the base will be higher near the emitter junction, as shown in figure 4.4. This does not reduce the electric field in the base to zero. A small residual field must remain after space charge neutralization to support the uneven distribution of electrons since they will tend to diffuse and equalize their distribution. For small collector currents, this field is also small so it has been neglected up to this point. However, as the collector current is increased, the distribution of current carriers in the base becomes more uneven necessitating an increase in this supporting field. It can be seen from figure 4.4 that in order to support a higher concentration of electrons at the emitter, the field must be positive toward the emitter and negative toward the collector. This field is in the correct direction to speed the holes across the base.

The increase in minority carrier velocity across the base increases the current gain because the change of recombination is lessened. This is shown as the initial increase in current gain in figure 4.8. This initial rise is more pronounced in an alloy junction transistor because the surface recombination term is quite important in the determination of its current gain. For good quality transistors, volume recombination is small so there is only a slight increase with the grown junction transistor which has negligible surface recombination.

After the initial increase, the current gain is found to decrease steadily. This is caused by a reduction in injection efficiency resulting from the increased electron concentration in the base.

As the collector current is increased to high levels, the injected-hole concentration in the base becomes markedly greater. This requires that the electron density increase far above its normal value in order to maintain space charge neutrality. This increased electron density near the emitter junction also increases the number of electrons injected into the emitter. Because these injected electrons will contribute only to the emitter and the base currents, not the collector current, the current gain of the transistor will fall off.

The variation of gain with collector current is of great importance in the application of transistors, particularly with power transistors which must supply large currents. The most practical method of maintaining current gain at high current levels is to dope the emitter as heavily as possible so that a large increase of the majority carrier density in the base can be tolerated before the injection efficiency drops to an unacceptable value. This is one reason why power transistors are usually the alloy junction type. The recrystalized semiconductor material near the emitter dot is normally saturated with the impurity contained in the dot so the emitter has a very low resistivity.

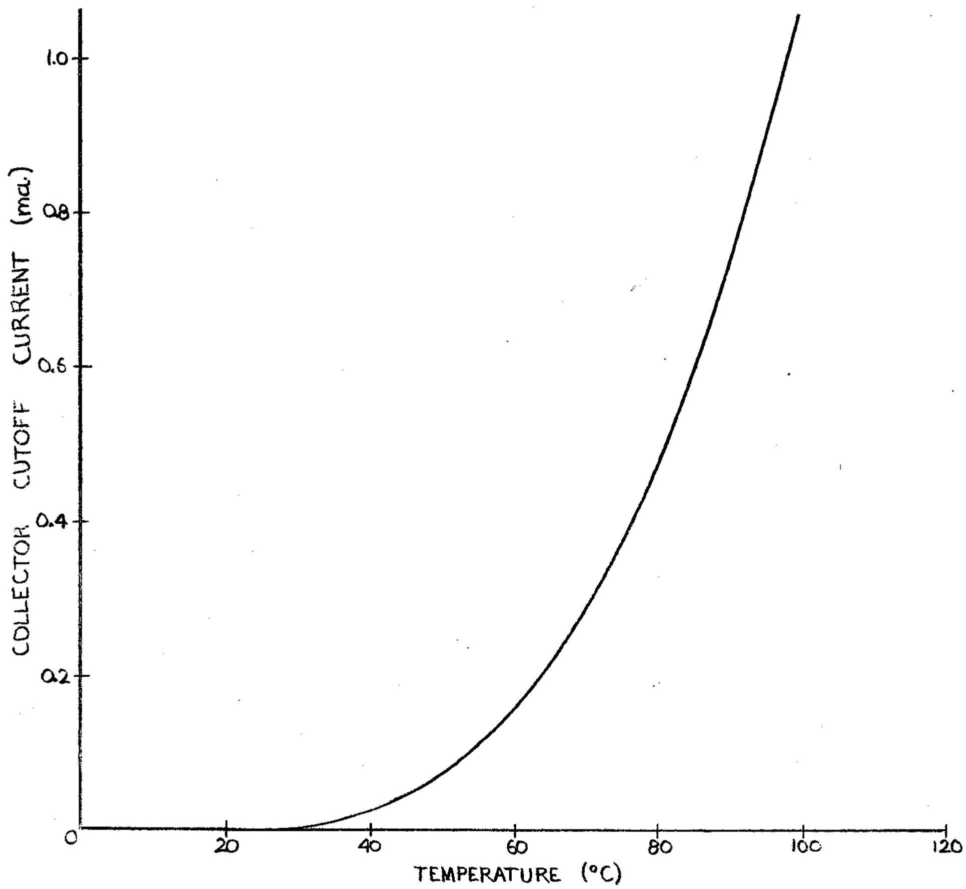


Figure 4.10. Plot of Collector Cutoff Current versus Temperature for a Germanium Transistor.

Variation of Current Gain With Collector Voltage. The resistivity of the collector material is usually considerably lower than the resistivity of the base material. Therefore, the depletion region of the collector junction must extend primarily into the base in order to expose an equal number of immobile impurity atoms on either side of the junction. Furthermore, when collector voltage is applied, the depletion region will become wider and will penetrate further into the base, narrowing the effective base width. This will increase both the emitter and transport efficiencies and will therefore increase the current gain of the transistor. Base width modulation by the collector voltage is illustrated in figure 4.3b, and the effect of collector voltage on current gain is plotted in figure 4.9.

TEMPERATURE DEPENDENCE

Since the properties of semiconductor materials vary widely with temperature, the performance of semiconductor devices, including the transistor, can be expected to be temperature sensitive. The temperature dependence of semiconductor materials has already been discussed at some length in Chapter 2. It has been shown that the thermal generation of hole-electron pairs increases rapidly with temperature and will eventually cause a doped semiconductor to loose its characteristic properties as the number of thermally generated carriers becomes appreciable compared to the number of majority carriers in the material. Furthermore, it was pointed out that the mobility of the carriers decreases with increasing temperature because of the increased thermal vibrations of the crystal lattice. Finally, it was explained that the thermal energy of the current carriers increases with temperature which strongly affects diffusion phenomena. It turns out that the diffusion current for a given density gradient increases with temperature as does the diffusion length.

Collector Cutoff Current. Since the collector junction is reverse biased, the thermally generated minority carriers present in the base and the collector will diffuse to the collector junction and will be swept across the junction. These carriers will then produce a collector current, even though the emitter junction is not forward biased. This uncontrolled collector current is called the collector cutoff current.

Since the number of thermally generated minority carriers will increase rapidly with temperature, so will the collector cutoff current. This is illustrated in figure 4.10 which is a plot of collector cutoff current as a function of temperature. At normal operating temperatures, this current is quite small, if not negligible; but at higher temperatures, it will exceed the normal operating current of the device. When this happens, the emitter junction will loose its control of the collector current, and the transistor becomes useless as an amplifier.

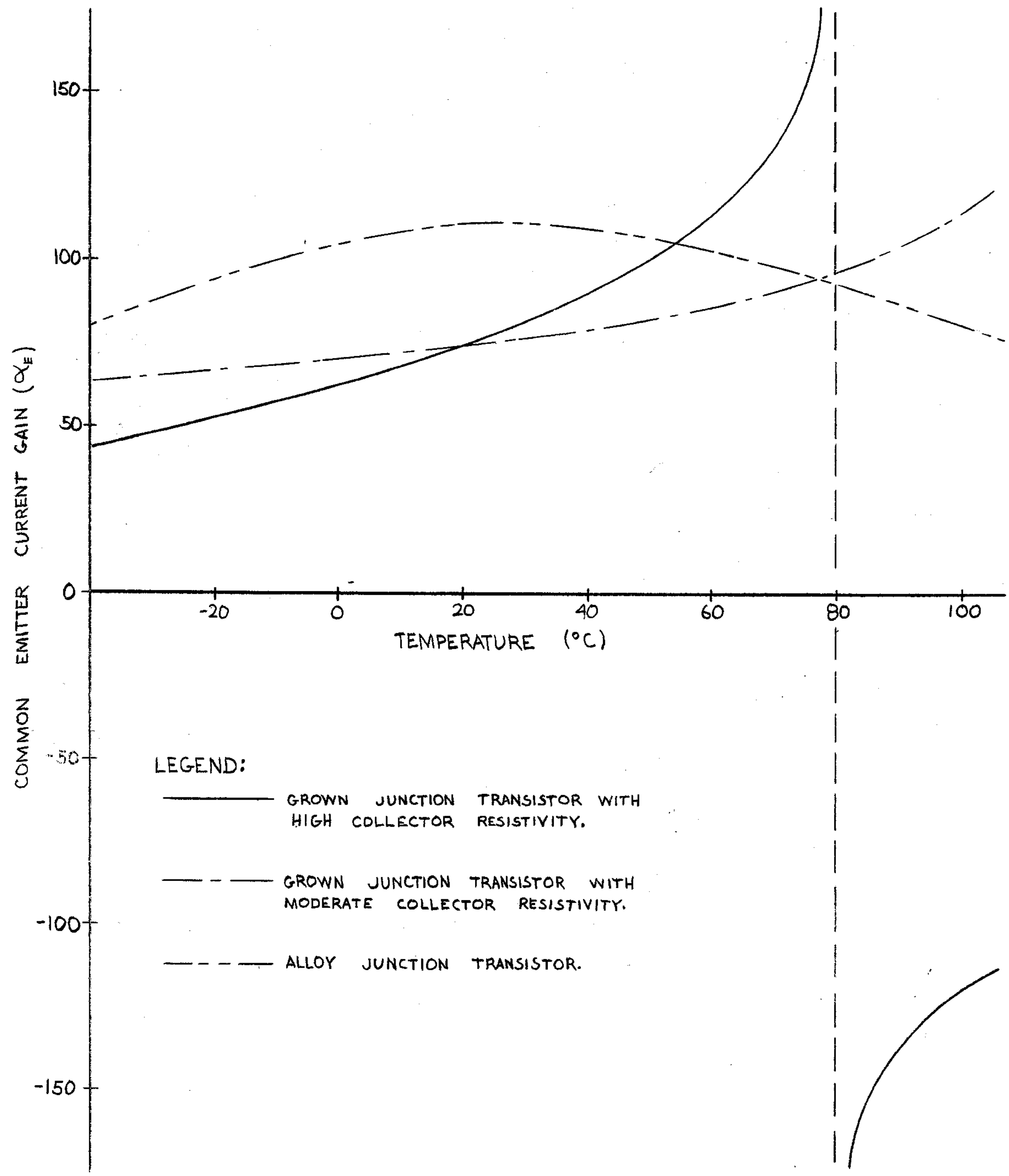


Figure 4.11. Variation of Common Emitter Current Gain with Temperature for Different Transistors.

Reduction of Emitter Junction Resistance. For a given forward bias voltage, only a certain number of majority carriers have enough thermal energy to diffuse across the lowered barrier of the emitter junction. However, the average energy of these carriers will increase with temperature so a greater number can cross the junction. This gives an increase in current with no increase in voltage, or a reduction in the emitter junction resistance. This takes place over the entire temperature range of the transistor, and it therefore has a pronounced effect on its biasing.

Effect of Temperature on Current Gain. Figure 4.11 shows the variation of current gain with temperature for several types of transistors. The causes of these changes will be discussed in relation to the emitter, transport, and collector efficiencies.

The emitter efficiency is not greatly affected by temperature. Temperature affects the injection efficiency of NPN and PNP transistors differently because the mobility of holes is reduced more than the mobility of electrons at higher temperatures. The net effect is that at elevated temperatures there is a slight increase in the injection efficiency of NPN transistors while that of PNP transistors remains essentially constant.

In a grown junction transistor, the transport efficiency generally increases with temperature. The higher thermal energy of the current carriers speeds diffusion through the base, which lessens the chance of recombination. However, the transport efficiency in an alloy junction transistor might well deteriorate at higher temperatures because of increased surface recombination. The variations in the current gain of an alloy junction transistor shown in figure 4.11 are probably caused by changes in the transport efficiency. At first, the current gain increases with temperature because of the more rapid diffusion through the base; but at higher temperatures, surface recombination predominates, reducing the current gain.

If the collector is made of highly doped semiconductor material, the collector efficiency will be very close to unity over the entire temperature range of the transistor. This is true for an alloy junction transistor. However, in a grown junction unit, the resistivity of the collector is frequently not much higher than that of the base. In this case, as was mentioned before, the holes drawn into the collector (of a PNP transistor) can produce a significant increase in the hole concentration near the collector junction. This will give rise to an electric field which will act on the thermally generated electrons in the collector speeding them toward the junction. These electrons will be swept across the collector junction into the base and will contribute to the collector current, but not to the emitter current. The number of thermally generated electrons in the collector will increase with temperature and so will the collector current. Therefore, the collector efficiency, and also the current gain, will increase with temperature.

At a sufficiently high temperature, the collector current can become greater than the emitter current, whereupon the direction of the base current will reverse. This is the cause for the instability of the current gain shown in figure 4.11 (solid line).

In general, the current gain of a grown junction transistor will increase with temperature since both the transport and the collector efficiencies increase. Furthermore, if the collector resistivity is comparable to that of the base, the current gain can become unstable at elevated temperatures. The current gain of an alloy junction transistor, however, can vary in almost any fashion depending on the relative importance of the surface and volume recombination terms. The curve given in figure 4.11 is only one possible example.

Conclusions. Practically all the temperature effects mentioned act in such a way as to increase collector current at higher temperatures. As the collector current increases so does the power dissipation at the collector junction. This produces further heating and could lead to a cumulative condition known as thermal runaway, which would ultimately destroy the unit. Therefore, transistor circuits require some method of bias stabilization on compensation to maintain a reasonably constant collector current over the operating temperature range.

COLLECTOR BREAKDOWN VOLTAGE

The reverse biased collector junction of a transistor is subject to avalanche or zener breakdown as was the case with the junction diode. A third type of breakdown known as collector punch through is also possible. On the other hand, the emitter junction is normally forward biased so its reverse breakdown voltage is of little concern.

The base of a transistor is a thin layer of high resistivity material, while the collector resistivity is usually very much lower. Therefore, the depletion region of the collector junction will extend primarily into the base; and it will become wider as collector voltage is increased. At high collector voltages, it is possible for the depletion region to penetrate through the base to the emitter junction, thereby providing a direct conducting path between the emitter and the collector. This is known as collector punch through. As with the other breakdown mechanisms, collector punch through will not injure the transistor unless the power dissipation becomes great enough to cause thermal damage.

The breakdown mechanism in alloy junction transistors is almost always collector punch through. However, in grown junction units the collector resistivity may not be much greater than the base resistivity. In this case, the depletion region will penetrate into both the collector and the base regions; and the device will usually undergo avalanche breakdown before punch through occurs.

Zener breakdown is rarely found in a transistor. The high resistivity of the base material makes for a wide depletion region so that intense fields are not built up across the junction. Zener breakdown only occurs in PN junctions where both materials are heavily doped.

HIGH FREQUENCY OPERATION

The transistor has some rather severe high frequency limitations. Alloy junction transistors are restricted to operation below a few hundred kilocycles, and grown junction units will not operate above a few megacycles. (However, special constructions can be used which will function at frequencies higher than 500 megacycles.) The reasons for these limitations and some of the techniques used to improve high frequency performance will be investigated here.

Transit Time. Since the transport of minority carriers through the base takes place by rather slow diffusion processes, it will take an appreciable length of time for a signal applied to the emitter junction to reach the collector junction. When a signal is applied to the input of a transistor, it will modulate the number of minority carriers injected into the base and alter the minority carrier density in the base above and below the no-signal value. If the input frequency is made sufficiently high, the amplitude (or phase) of this signal will vary with distance through the base because of the finite transit time. Figure 4.12, which is a plot of minority carrier density with distance through the base, illustrates this point.

In the time it takes for the signal to move through the base, the random diffusion forces will act to equalize these density variations as shown in the figure. Hence, the amplitude of the signal reaching the collector is considerably lower than that at the emitter junction. This results in a low current gain at higher frequencies.

Diffusion Capacitance. If a voltage step is applied to the input of a transistor, the collector current will not rise immediately because of the finite transit time across the base. Furthermore, the collector current step will not have a sharp leading edge because of the diffusion that takes place during the transport process. These effects are shown in figure 4.13. Attention will now be focussed on the input circuit to show another phenomenon associated with transit time.

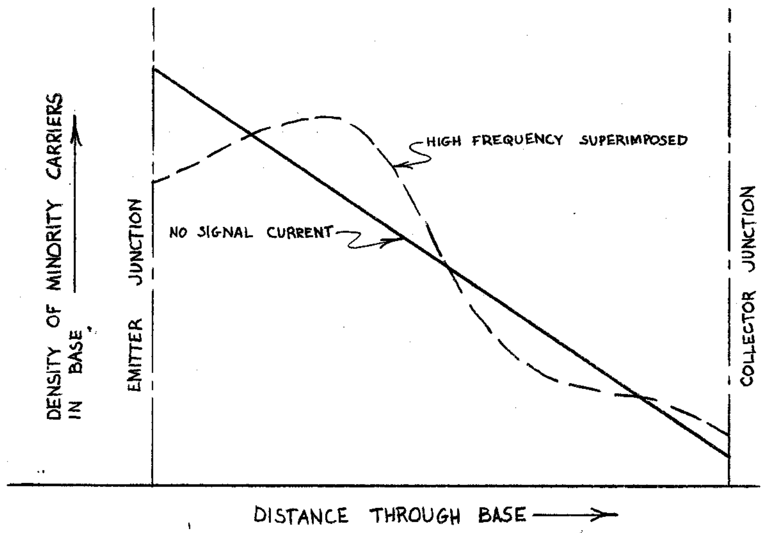


Figure 4.12. Illustrating the Reduction in A-C Current Gain at High Frequencies by Diffusion Which Equalizes Density Variations, a Consequence of the Finite Transit Time across the Base.

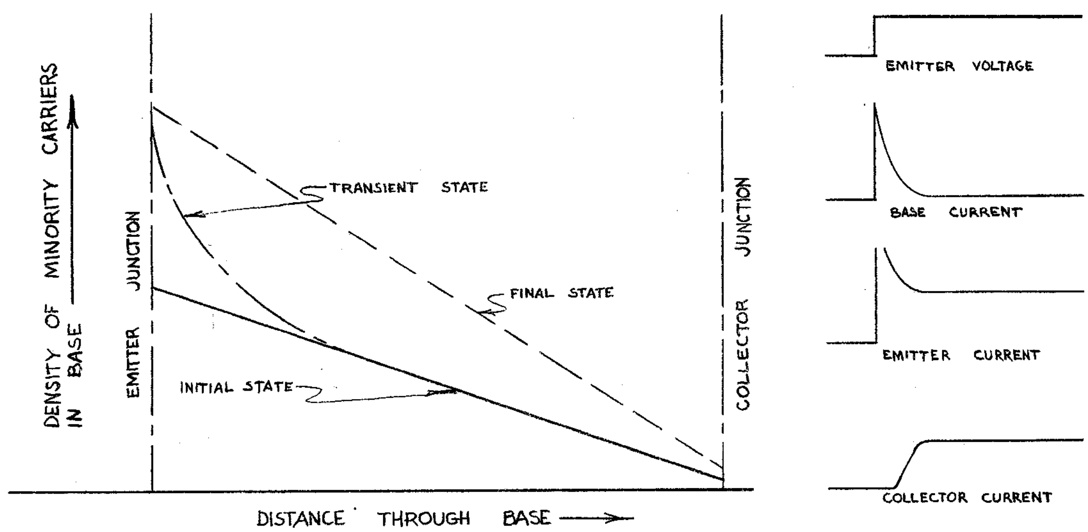


Figure 4.13. Effect of a Sudden Increase in Input Voltage on Minority Carrier Distribution in Base. Emitter, Base, and Collector Current Waveshapes also Given.

When the voltage step is applied to the emitter junction, the minority carrier concentration in the base will increase, or the base will become charged. To charge the base region, an excess of minority carriers must be injected into the base over the emitter junction. Moreover, an equal number of majority carriers must be drawn in at the base terminal to preserve space charge neutrality. These excess charges will not contribute to the collector current but will be stored in the base until the bias on the emitter junction is again decreased. Hence, the emitter-base terminals of the transistor will appear as if they were shunted by a capacitance. This capacitive effect, since it is associated with the diffusion of minority carriers through the base, is referred to as diffusion capacitance.

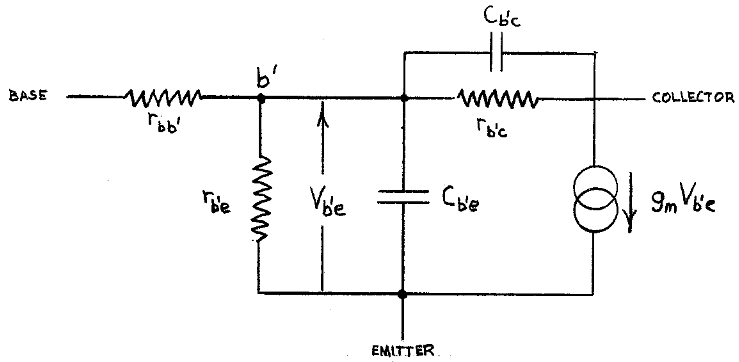
The voltage step applied to the input of the transistor will produce a transient current in the emitter and the base leads which charges the diffusion capacitance. In the transient state, the emitter current will be greater than the final emitter current because the diffusion gradient near the emitter junction (which determines the emitter current for a given forward bias) is greater than the gradient produced by the final current. This is shown in figure 4.13. The initial base current will also be considerably greater than its final value because majority carriers must flow in at the base terminal to preserve space charge neutrality.

It can also be shown, in a similar manner, that a reverse transient current will flow in the base and emitter to discharge the base when the emitter junction bias is decreased.

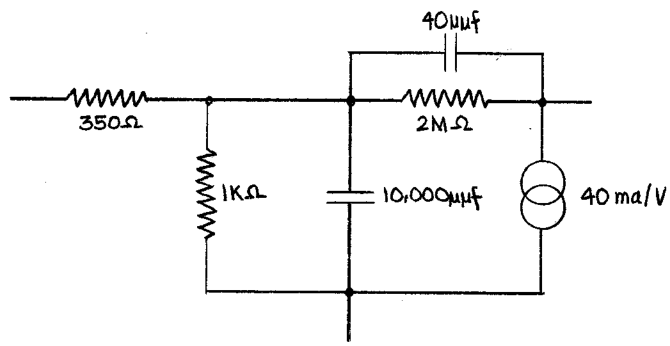
The diffusion capacitance will lower the input impedance of the transistor at high frequencies. The signal source driving the transistor must produce a current that alternately charges and discharges the base rather than producing a collector current. This represents a loss of input signal and lowers the effective amplification of the the device.

Base Spreading Resistance. The base spreading resistance is the resistance of the material between the base contact and the active area of the emitter junction. This resistance appears electrically in series with the base terminal.

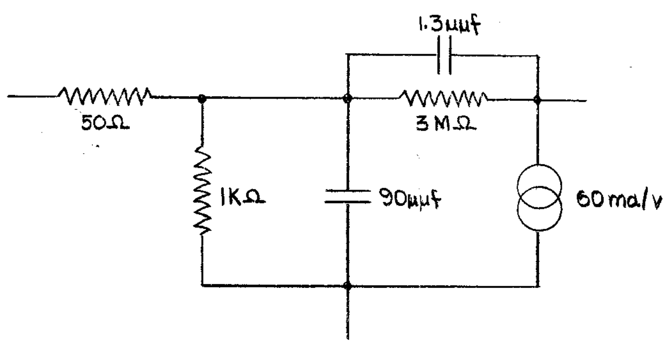
Since the base is made of high resistivity material and is normally very thin, the base resistance can be quite large (several hundred ohms). Hence, a signal applied between the emitter and the base terminals will be attenuated by the base resistance before it reaches the emitter junction. Furthermore, since the emitter junction impedance decreases at high frequencies because of the diffusion capacitance, the signal reaching it will be even smaller at high frequencies.



a. General Equivalent Circuit.



b. Equivalent Circuit of a Low Frequency Alloy Junction Transistor.



c. Equivalent Circuit of a High Frequency Drift Transistor.

Figure 4.14. Equivalent Circuit Useful in Evaluating High Frequency Performance of a Transistor. Specific Examples are Included.

Collector Junction Capacitance. The collector depletion region forms an insulator between the conducting base and collector regions, so the reverse biased collector junction will behave capacitively. This collector junction capacitance is considerably less than the diffusion capacitance; but it shunts the high impedance collector junction, while the diffusion capacitance shunts the low impedance emitter junction. Hence, at high frequencies, the collector capacitance will frequently cause a greater loss of overall gain by shunting the output signal than will the diffusion capacitance by shunting the input signal. This capacitance also provides a feedback path between the collector and the base so it can produce degeneration or instability at higher frequencies when the common emitter configuration is used.

An Equivalent Circuit. The effect of the base resistance, the diffusion capacitance, and the collector capacitance on the high frequency performance of a transistor can be evaluated with the aid of the equivalent circuit shown in figure 4.14a. The elements of this equivalent circuit can be identified as: base resistance ($r_{bb'}$), emitter junction resistance ($r_{b'e}$), diffusion capacitance ($C_{b'e}$), collector junction resistance ($r_{b'c}$), collector capacitance ($C_{b'c}$), and the equivalent-circuit current generator ($g_m V_{b'e}$); the terminal b' is the internal base terminal (near the active portion of the emitter junction), g_m is the transfer conductance (a quantity relating the emitter junction voltage $V_{b'e}$ to the collector current), and $V_{b'e}$ is the voltage on the internal base terminal (emitter junction).

This equivalent circuit does not take into consideration the delay and reduction in current gain caused by transit time across the base so this circuit is not valid where this is the limiting factor of high frequency performance. For most transistors, though, this circuit is adequate over the useful frequency range of the device.

Figure 4.14 shows that the portion of the input voltage appearing at the emitter junction (internal base terminal) will depend on the base resistance, the emitter resistance, the diffusion capacitance, and the signal frequency. The base resistance is generally less than the emitter resistance so at low frequencies practically all of the applied voltage will appear at the internal base and will be effective in producing an output. At high frequencies the reactance of the diffusion capacitance will drop, resulting in an additional attenuation of the input signal. It is therefore desirable to minimize the base resistance and the diffusion capacitance.

Some of the output signal appearing on the collector is fed back to the base through the collector capacitance. Since the collector voltage is out of phase with the base voltage (for a resistive load) this constitutes negative feedback and reduces the useful gain of the transistor. If the transistor is working into an inductive load, this feedback can become positive, possibly introducing instability.

The equivalent circuits of a low frequency alloy junction transistor and a high frequency drift transistor are given in figure 4.14. The maximum useful frequency of the former is in the order of 500 kc while that of the latter is about 100mc. The drift transistor has a lower base resistance, diffusion capacitance, and collector capacitance which permits operation at higher frequencies.

Improving High Frequency Performance. Some of the physical parameters of an alloy or grown junction transistor can be altered to raise the upper frequency limit. These are reducing the base width, using a low resistivity base material, and reducing the cross-sectional area of the device. Of course, this is not an inclusive list; but it represents some of the readily availiable means.

A reduction in base width will decrease transit time and diffusion capacitance as well as increase the transport and injection efficiencies. The reason for the decrease in transit time should be obvious, and the decrease in diffusion capacitance results because a narrower base will store less charge. The increase in transport and injection efficiencies have been explained previously. A thin base does produce one undesirable result: the base spreading resistance is increased because of the narrower current path between the active area of the emitter junction and the base contact. Nonetheless, this is more than compensated for, particularly at high frequencies, by the reduction in transit time and diffusion capacitance.

Reducing base width is a very effective method of improving transistor performance; however, with alloy and grown junction transistors, base widths less than 0.001 inch are difficult to produce which limits the usefulness of the method.

The use of a low resistivity base material will reduce both the base resistance and the injection efficiency. But if a transistor already has a high injection efficiency, a lower resistivity base can give a significant improvement in high frequency performance at a small sacrifice in low frequency gain. This technique is particularly useful in the design of video amplifiers where a flat frequency characteristic is more important than high gain.

Since the collector capacitance is directly proportional to the collector junction area, this area should be as small as possible for optimum high frequency performance. A smaller cross-sectional area can also reduce the base resistance (depending on the geometry of the transistor) by reducing the average distance between the base terminal and the active portion of the emitter junction. This is particularly true for grown junction transistors. On the other hand, a reduction in the cross-sectional area will also reduce the current capacity and maximum power dissipation of the device. Furthermore, if the transistor is made too small it will be fragile and difficult to manufacture.

SPECIAL TRANSISTORS

Thus far the discussion on transistors has been relatively general. The phenomena described applies to the majority of transistors, even though only the grown and the alloy junction transistors were mentioned. In this section, special designs which have been employed to improve the performance of the basic transistor will be covered. Furthermore, other PN junction devices - which operate quite differently from the basic transistor will be explained.

The Tetrode Transistor. The tetrode transistor differs from an ordinary grown junction transistor in that two separate base contacts are used. These contacts are located on opposite sides of the base as shown in figure 4.15. In operation, the emitter junction is forward biased by one of these base terminals (B_1) and reverse biased by the other (B_2). Therefore, minority carriers will be injected into the base near the forward terminal only. This reduces the average distance from the active area of the emitter junction to the B_1 terminal and the base spreading resistance when B_1 is used as the input terminal.

A cross-base current will flow between the two base terminals since there is a potential difference between them (for a NPN transistor, B_1 is about 0.5 volts and B_2 about -1.5 volts with respect to the emitter). However, the cross-base current will be small because the base is made of high resistivity material.

The electric field set up by the cross-base bias will draw the minority carriers, diffusing across the base, toward the B_1 terminal. Thus, a number of these carriers, depending on the bias, will reach the base terminal and not the collector junction. This will decrease the low frequency current gain; but it is not a serious limitation since, at high frequencies, the reduction in current gain is more than compensated for by the reduction in base spreading resistance. This is proven in figure 4.16 which gives plots of the low frequency current gain, base spreading resistance, and 150 megacycle power gain as a function of cross-base current.

Another advantage of the tetrode transistor is that the B_2 terminal can be used to electrically control the gain of the device. This provides a convenient method of applying automatic gain control to a r-f amplifier. Furthermore, since the cross base bias will affect the low and high frequency gains differently, it can be used

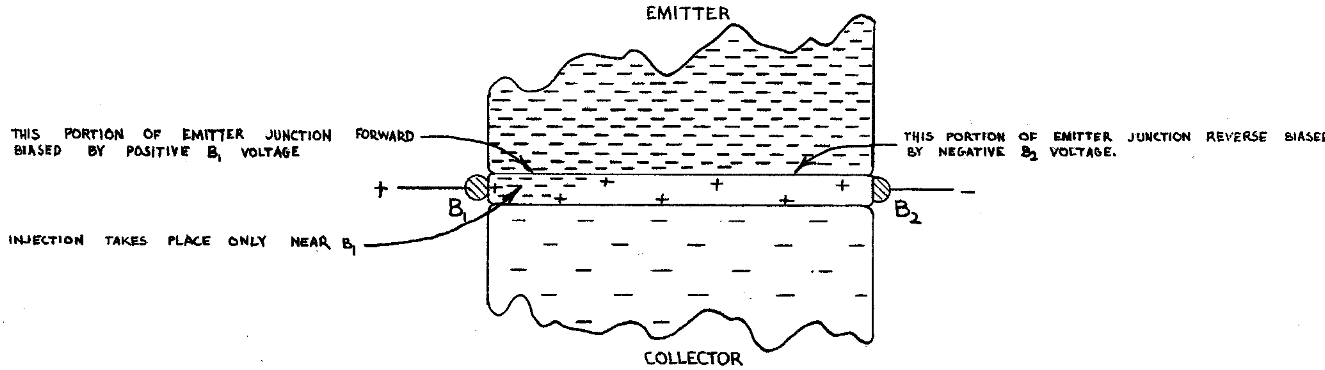


Figure 4.15. Path of Minority Carriers through the Base of a Tetrode Transistor Showing Reduction in Base Spreading Resistance.

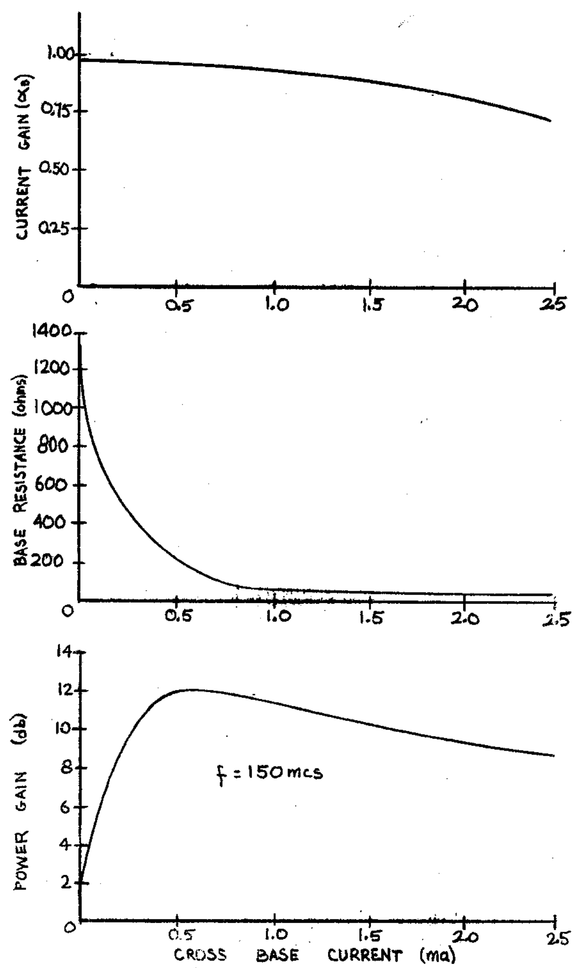


Figure 4.16. Effect of Cross Base Bias on the Characteristics of a Tetrode Transistor.

to produce a reasonably flat frequency response in video amplifiers by reducing the low frequency gain to equal the high frequency gain.

<u>The Drift Transistor.</u> It was stressed previously that the transport of minority carriers across the base is accomplished by the relatively slow process of diffusion with little or no aid from an electric field. In the drift transistor, the transport is greatly accelerated by establishing a built in electric field across the base in such a direction as to speed the carriers from emitter to collector. The electric field is created during fabrication by doping the base material rather heavily near the emitter junction and tapering off the impurity concentration with distance toward the collector junction. The majority carriers will tend to equalize their distribution because of thermal diffusion, but the impurity atoms are fixed in the crystal lattice. Therefore, there will be an initial diffusion of majority carriers toward the collector junction. This will continue until the charge unbalance sets up an electric field which opposes further diffusion. An equilibrium is reached with an excess of impurity ions near the emitter junction and an excess of majority carriers near the collector junction. This is illustrated in figure 4-17.

The electric field created in the base, opposing the diffusion of majority carriers from emitter to collector, will be in the correct direction to accelerate the minority carriers through the base since they have an opposite charge.

Considering, as an example, a NPN drift transistor, the acceptor concentration in the P-type base will be high near the emitter junction but low near the collector junction. The higher concentration of holes near the emitter will cause diffusion toward the collector. When equilibrium is reached, there will be an excess of holes near the collector and an excess of negative acceptor ions near the emitter. Hence, an electric field will be established in the base, positive toward the collector and negative toward the emitter. When electrons are injected into the base, they will be accelerated to the collector junction by this field.

In addition to reducing the transit time, the drift field materially reduces diffusion capacitance. Since the minority carriers move faster through the base, a lesser number is required to produce a given collector current. Therefore, less charge will be stored in the base. This is shown in figure 4.18.

Another advantage of the drift transistor is that the base resistance is reduced by the high impurity concentration near the emitter junction which gives a low resistivity path for the base current. Although this might seem to reduce the injection efficiency, it must be remembered that the minority carriers injected

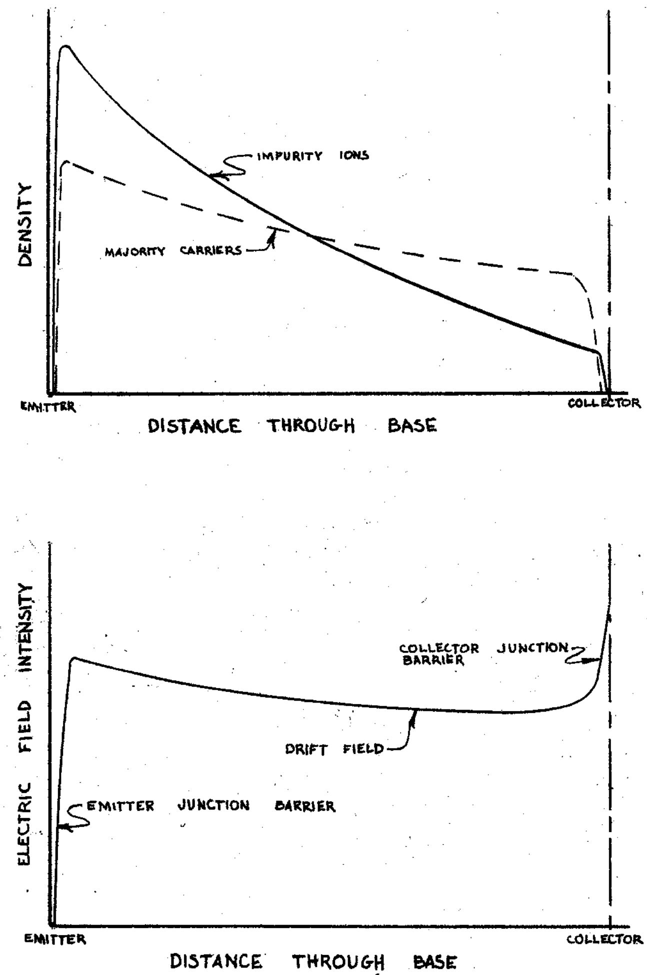


Figure 4.17 Illustrating Formation of a Built in Electric Field in the Base of a Drift Transistor, Having an Uneven Impurity Distribution, by the Initial Diffusion of Majority Carriers.

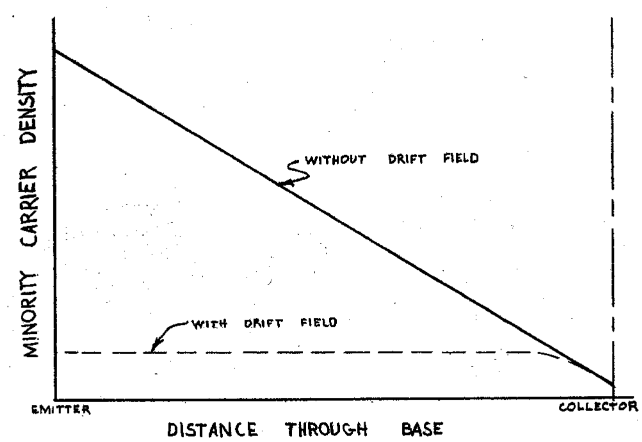


Figure 4.18 Comparison of the Minority Carrier Concentrations in the Base of a Transistor Required to Produce a Given Collector Current with and without the Drift Field.

into the base are acted upon by the drift field and are therefore more effective in producing an emitter current than are the minority carriers injected into the emitter which must diffuse away from the junction. Therefore, even if an equal number of carriers cross the junction in either direction, the injection efficiency can still be high.

The graded base resistivity of the drift transistor also assists in lowering the collector capacitance since the high resistivity material near the collector junction makes for a wide depletion region.

The merit of the drift transistor can be seen by comparing the equivalent circuits given in figure 4.14.

At high current levels where the concentration of injected carriers becomes greater than the majority carrier concentration, the performance of the drift transistor will deteriorate; and it will operate as a diffusion transistor. This happens because of the distortion of the drift field by the injected carriers. It is on indirect result of space charge neutralization.

The graded base resistivity of the drift transistor is not as difficult to produce as might be thought. This type of resistivity profile is the natural outcome of many fabrication processes as will be seen in the next chapter.

The Intrinsic Transistor. In the intrinsic transistor, a layer of undoped (intrinsic) semiconductor is sandwiched between the collector and the base. This gives a PNIP (or NPIN) structure as shown in figure 4.19. Since this layer contains no current carriers, the collector depletion region will extend through the intrinsic material from the collector to the base. This produces a wide depletion layer, greatly reducing the collector capacitance.

The intrinsic layer can be made quite thick, yet it will not appreciably increase the transit time: a strong electric field, produced by the collector voltage, exists in this region; this field speeds the carriers through the intrinsic layer much more rapidly than the diffusion forces take them through the base.

To appreciate the advantage of the intrinsic transistor, it must be remembered that the collector junction capacitance provides a feedback path from collector to base. This greatly reduces the gain of a transistor operating as a wide band video amplifier and requires that neutralization be provided for high frequency tuned amplifiers (common emitter). In the case of a video amplifier very little can be done to compensate for this feedback; and neutralization of tuned amplifiers cannot always be accomplished conveniently, nor is it entirely effective because of base spreading

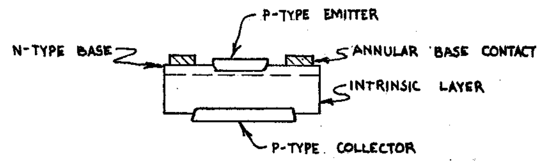


Figure 4.19. Construction of an Intrinsic Transistor, Emitter and Collector Alloyed onto Partially Doped N-Type Base.

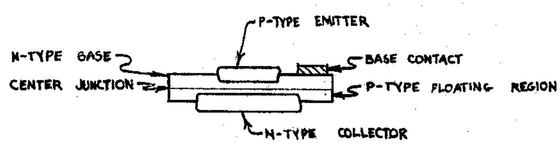


Figure 4.20. Construction of a Hook Junction Transistor, Emitter and Collector Alloyed onto a Grown PN Junction.

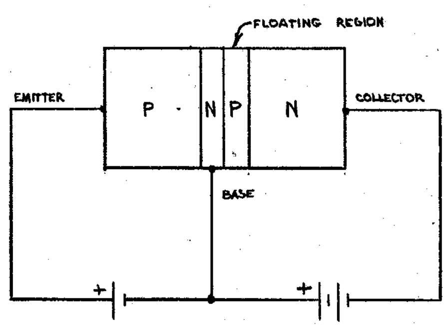


Figure 4.21. Bias Circuit for a Hook Junction Transistor.

resistance. Therefore, a reduction in collector capacitance is of considerable importance.

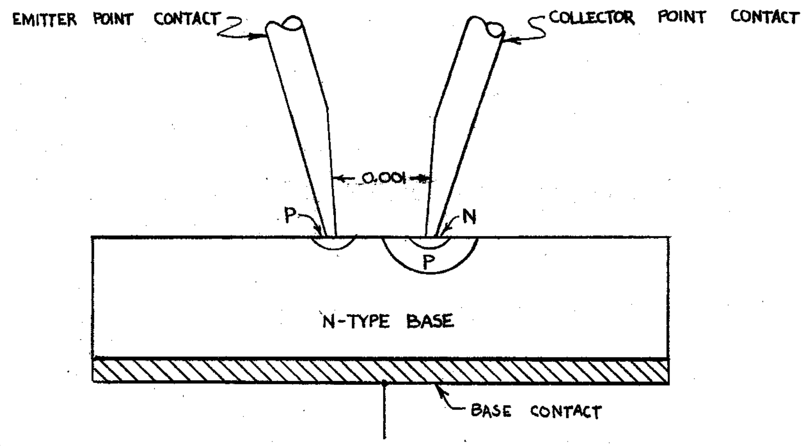
At the present time it is difficult to obtain intrinsic material of sufficient purity, so this principle cannot be fully utilized. Even a low concentration of impurities in the intrinsic layer will restrict the width of the depletion region and result in poor performance. Nonetheless, some of the advantages of the intrinsic transistor can be exploited by using graded junctions, i.e. junctions where the transition from N to P-type is gradual. This will widen the depletion region somewhat, reducing collector capacitance and increasing the collector breakdown voltage.

<u>The Hook Junction Transistor.</u> Departing now from high frequency transistors, a junction transistor that exhibits a common base current gain considerably greater than one will be described.

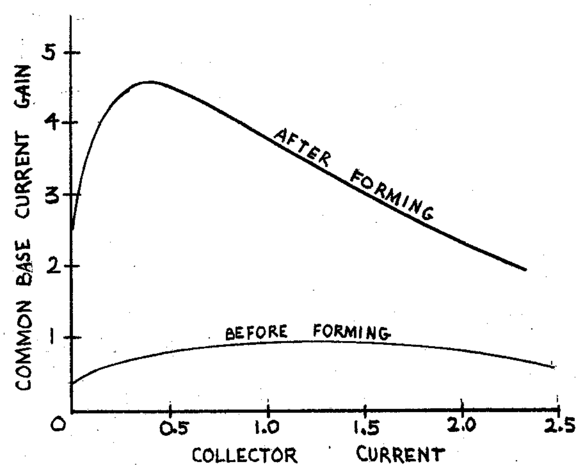
Ordinarily, in a two-junction transistor, the common base current gain will approach unity, values of 0.7 to 0.99 being common. In the avalanche transistor which is a junction transistor operating with the collector junction near avalanche breakdown, the common base current gain will be about 5 because of carrier multiplication in the collector depletion region. The hook junction is capable of giving common base current gains in the order of 100.

The hook junction transistor employs a PNPN (or NPNP) structure as shown in figure 4.20. Connection is made to the emitter, base, and collector; but the P region between the base and collector is left electrically floating. Furthermore, both center layers are thin in comparison to the diffusion length in the material, and the resistivity of these layers is considerably higher than that of either the emitter or the collector.

The biasing arrangement for a hook junction transistor is shown in figure 4.21. The center junction is reverse biased; the emitter and base function as usual. When the emitter junction is forward biased, holes will be injected into the base and will diffuse to the reverse biased center junction. The holes will then be swept into the floating region. These holes will not be free to diffuse into the collector since the collector junction is not forward biased and a barrier to holes still exists. However, the collector junction will become forward biased as the hole concentration in the floating region increases, since the excess holes make the floating region positive with respect to the collector. This forward bias will enable some of the holes to diffuse into the collector, and it will also permit electrons from the collector to diffuse into the floating region. (Note: these electrons will not eliminate the forward bias on the collector junction; enough holes will be retained in the floating region to maintain a forward bias condition.)



a. Possible Structure Produced by Forming Process.



b. Current Gain Before and After Forming.

Figure 4.22. The Point Contact Transistor.

These electrons will diffuse across the floating region to the center junction and will be swept into the base. Hence, a collector current will be produced both by the holes leaving the base and by the electrons swept into the base. It remains to be shown that the electron current is very much greater than the hole current, which would indicate that the collector current is much greater than the emitter current.

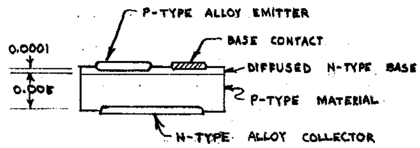
Since the concentration of electrons in the collector is considerably greater than the concentration of holes in the floating region, the number of electrons crossing the collector junction will greatly exceed the number of holes. Furthermore, since the width of the floating region is less than the diffusion length for holes in the collector, the diffusion current produced by a given number of electrons will be greater than the current produced by an equal number of holes, (see section on injection efficiency). It can be seen, then, that the total collector current will be much larger than the original emitter current producing it.

Although some of the electron current reaching the base from the collector do produce an emitter current, the increase in emitter current will be small. The diffusion of electrons across the emitter junction is inhibited by the remaining barrier even though this junction is forward biased. The electrons are preferentially swept out the base terminal because no barrier exists along this path.

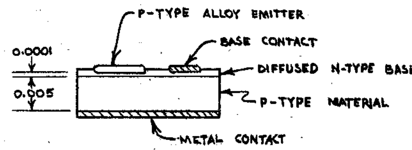
The hook junction transistor has not seen much application. The biggest reason for this is probably the difficulty encountered in producing such a device. It is not easy to obtain reproducable results in two junction units on a production basis, and the problems associated with a multiple junction transistor can be expected to be considerably greater.

<u>The Point Contact Transistor.</u> Although the point contact transistor was the first to appear, its operation never has been well understood. A point contact transistor is made by bringing two fine, pointed wires into contact with the surface of a N-type semiconductor wafer, the spacing between the wires being in the order of 0.001 inch. The contact between these wires and the semiconductor is a rectifying junction, and it is supposed that the emitter injects minority carriers into the base which diffuse to the collector. This explanation is very similar to that for a junction transistor, except that one irregularity exists: the common base current gain of a point contact transistor is usually greater than one. This is not in agreement with junction transistor theory.

The explanation most frequently offered to explain the high current gain of a point contact transistor is that a hook collector is created during a forming process. The forming process usually consists of heating the collector point to a very high temperature



a. PNPN Triode.



b. PNPM Triode

Figure 4.23. Construction of the PNPN and PNPM Thyratron Transistors.

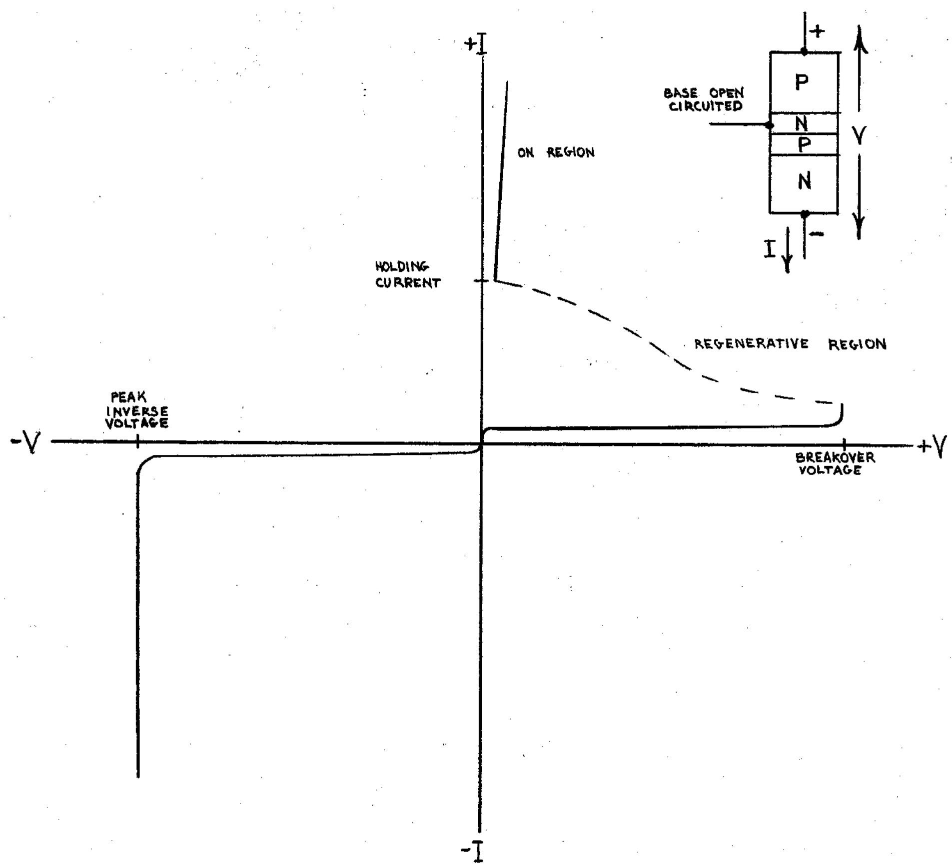


Figure 4.24. Breakdown Characteristics of a Thyratron Transistor, Base Open Circuited.

for a short period of time. It is believed that this causes the conversion of the N-type base material near the collector junction into a hook structure as shown in figure 4.22. This seems plausible considering the current gains obtained before and after forming (figure 4.22) and considering that the impurities contained in the contact points greatly affect the results obtained.

At the present time the point contact transistor is considered obsolete. Shock and vibration can cause large changes im the electrical characteristics since it is difficult to fix the position of the contact points. Furthermore, the wide variation in the performance of individual units of the same type makes direct replacement of defective units impossible. Generally speaking, far superior performance can be obtained with grown junction transistors.

<u>The Thyratron Transistor.</u> Solid state devices have been built that display characteristics similar to those of a gas thyratron. These devices can be switched from a high resistance state to a low resistance state by a relatively small trigger signal. In addition, the solid state thyratron can also be turned off by the control signal.

One type of thyratron transistor has a PNPN structure similar to that of a hook junction transistor. This is shown in figure 4.23a. A thin, high resistivity P-type base is diffused into a N-type crystal which also has a high resistivity. A N-type collector is alloyed to the P-type crystal, and a P-type emitter is alloyed to the diffused layer. Hence, both the emitter and the collector have a low resistivity. An ohmic contact is included on the base which is made very thin to give a fast switching action. The floating P region is made relatively thick, but its width (0.005 inch) is still small in comparison to the diffusion length of minority carriers in the material.

The operation of the thyratron transistor can best be described by considering its breakdown characteristics when a voltage is applied between emitter and collector, reverse biasing the center junction, and the base is left open circuited.

For voltages less than the breakdown voltage, the transistor will not conduct because of the blocking action of the center junction. This condition is represented by the off region in figure 4.24. However, when the breakover voltage is reached, the current will increase abruptly due to avalanche multiplication of the small reverse current through the reverse biased center junction. The holes and electrons generated in the center junction by avalanche multiplication will be swept into the central P and N regions by the barrier field. These carriers cannot diffuse across the collector

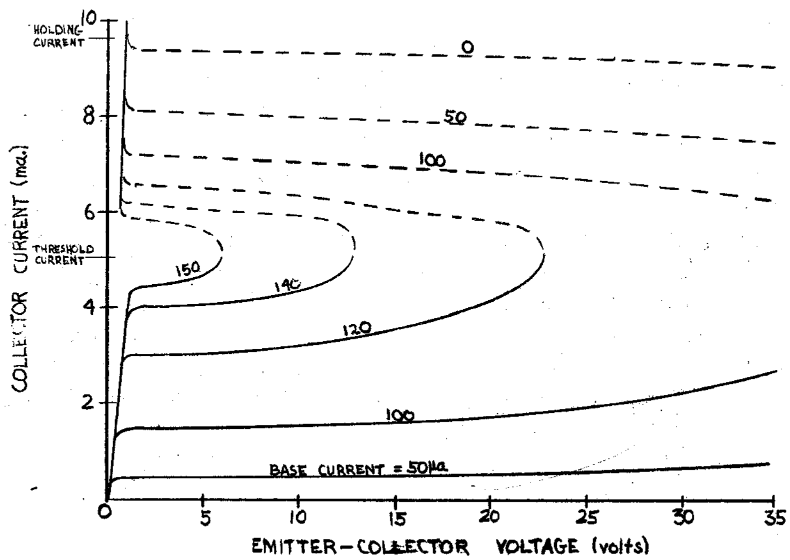


Figure 4.25. Turn On Characteristics of a Thyratron Transistor.

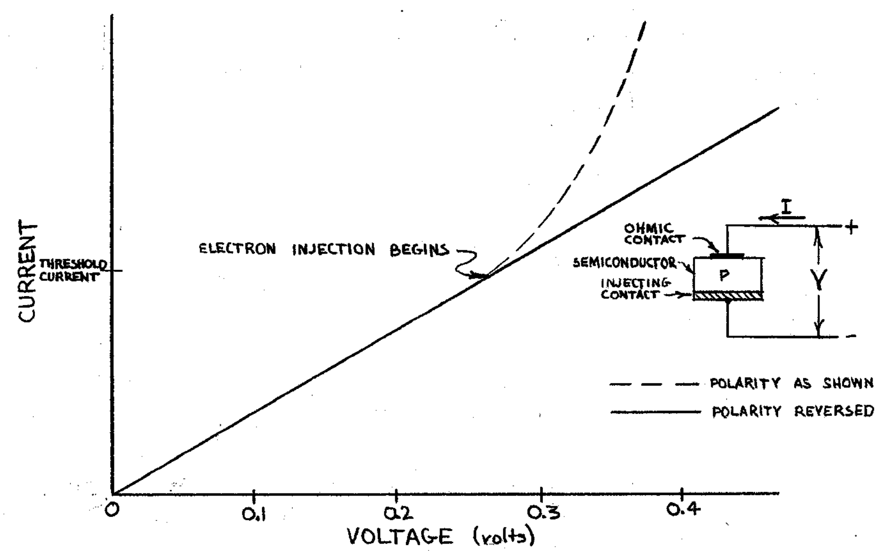


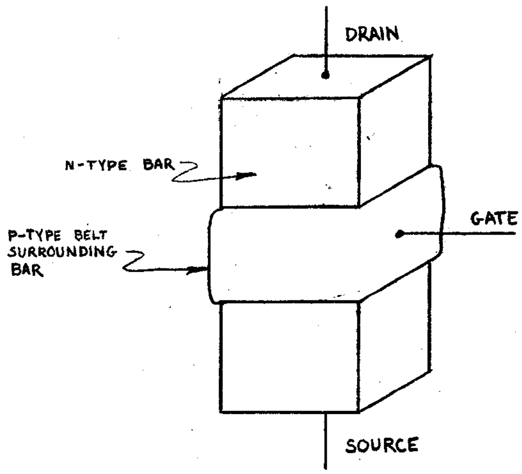
Figure 4.26. Volt-Ampere Curve for the Injecting Contact on a PNPM Thyratron Transistor for Both Directions of Current Flow

and emitter junctions because of the barriers existing there so they will set up a charge unbalance which reduces these barriers and forward biases both the collector and emitter junctions. Hence, the emitter will inject holes into the base which diffuse to the center junction. Likewise, the collector will inject electrons into the floating N region which will also diffuse to the center junction. This makes available at the center junction a far greater number of current carriers than are required to sustain the avalanche breakdown. Therefore, the voltage across this junction decreases with increasing current. This situation is represented by the regenerative region in figure 4.24. The voltage will continue to fall until the drop across the transistor is equal to that required to forward bias the emitter and collector junctions and make up for the ohmic losses in the material. In this condition, the device exhibits a very low resistance.

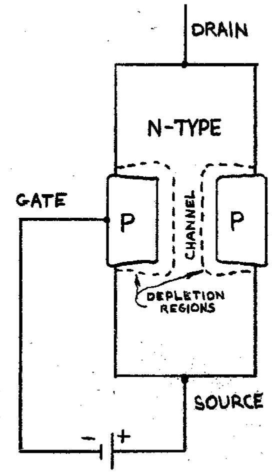
The thyratron transistor will remain in this conducting state until the current through it falls below the holding current. When this happens, the number of excess carriers in the central P and N region will be insufficient to forward bias the emitter and collector junctions so the transistor returns to the nonconducting state.

When a PNPN triode is in the off state, a small current does flow. This is the saturation current of the reverse biased center junction. This small current will produce a charge unbalance in the central P and N regions which forward biases the emitter and collector junctions, permitting the injection of carriers. However, these injected carriers will become trapped in recombination centers in the central P and N regions (i.e. crystal imperfections such as missing atoms in the lattice). As long as the carriers are not injected faster than the trapped carriers recombine, very few will reach the center junction; and the device will not switch into the conduction state. After the current reaches a certain level, the recombination centers become saturated. Then the injected carriers will diffuse to the center junction producing a drop in its resistance, switching the transistor into the on state.

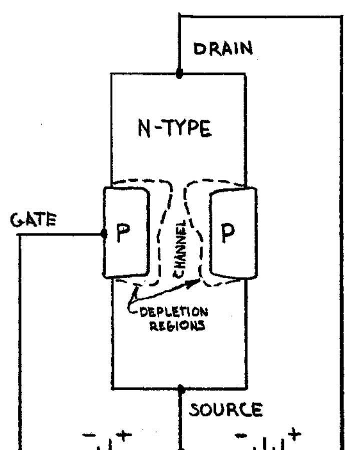
If the emitter-collector voltage is less than the breakover voltage, the PNPN transistor can be switched on by applying a trigger signal to the base that forward biases the emitter junction. Holes will then be injected into the base and will diffuse to the center junction, producing a collector current. If a large enough trigger is applied, the collector current will increase above the threshold value; and the collector will inject enough carriers into the floating region to saturate the recombination centers so the transistor will switch on.



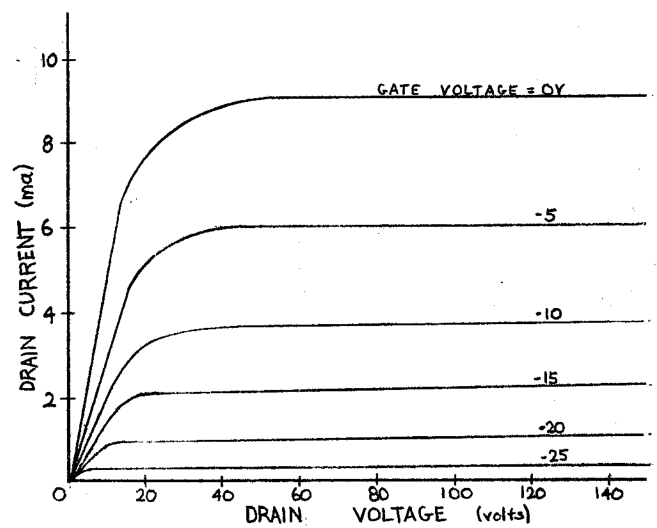
a. Construction of the Field Effect Transistor.



b. Narrowing of Channel by Depletion Regions.



c. Distortion of Depletion Region by Drain Voltage.



d. Characteristic Curves.

Figure 4.27. The Field Effect Transistor.

Figure 4.25 gives the turn on characteristics of a thyratron transistor. The characteristics are similar to those of an ordinary junction transistor as long as the collector current is below the threshold level. When collector injection starts, the transistor becomes regenerative and switches on.

If a reverse bias is applies to the emitter-base junction, the injection of holes by the emitter will be stopped. When this happens, holes will no longer be swept across the center junction into the floating region; and the forward bias on the collector junction will drop. Collector injection will then fall off, and the transistor will become nonconducting.

The PNPM transistor show in figure 4.23b differs from the PNPN transistor in that a metal-semiconductor contact is used as the collector. As long as the collector current is below a certain value, the metal contact is ohmic; and the device operates as a PNP transistor. However, when the current through the metalic contact is increased above a certain level, it injects electrons into the floating P region as would a N-type collector. When this happens, the PNPM triode will switch into a low resistance state.

The threshold current of the PNPM transistor is determined by the characteristics of the injecting metal contact, not by the presence of recombination centers in the floating P region. When a current is reached where the metal contact begins injecting, the transistor switches on.

The volt-ampere characteristics of the injecting contact are given in figure 4.26. The contact has a low resistance to current in either direction. However, at high currents, when the semiconductor is positive with respect to the contact, the contact is no longer ohmic; but it displays a sharp drop in resistance with increasing current. This is caused by the injection of electrons into the semiconductor from the metal.

<u>The Field Effect Transistor.</u> The construction of the field effect transistor is shown in figure 4.27a. A small, high resistivity N-type bar is surrounded by a belt of low resistivity P-type material. Ohmic contacts are made to both ends of the bar and to the P-type belt.

When this PN junction is reverse biased as shown in figure 4.27b, the depletion region will extend primarily into the bar because of its high resistivity. Therefore, the bias on this junction can control the resistance of the bar by modulating the width of the conducting channel between the depletion regions. Hence, if a voltage is placed across the bar as shown in figure 4.27c, the resulting current can be controlled by the junction bias.

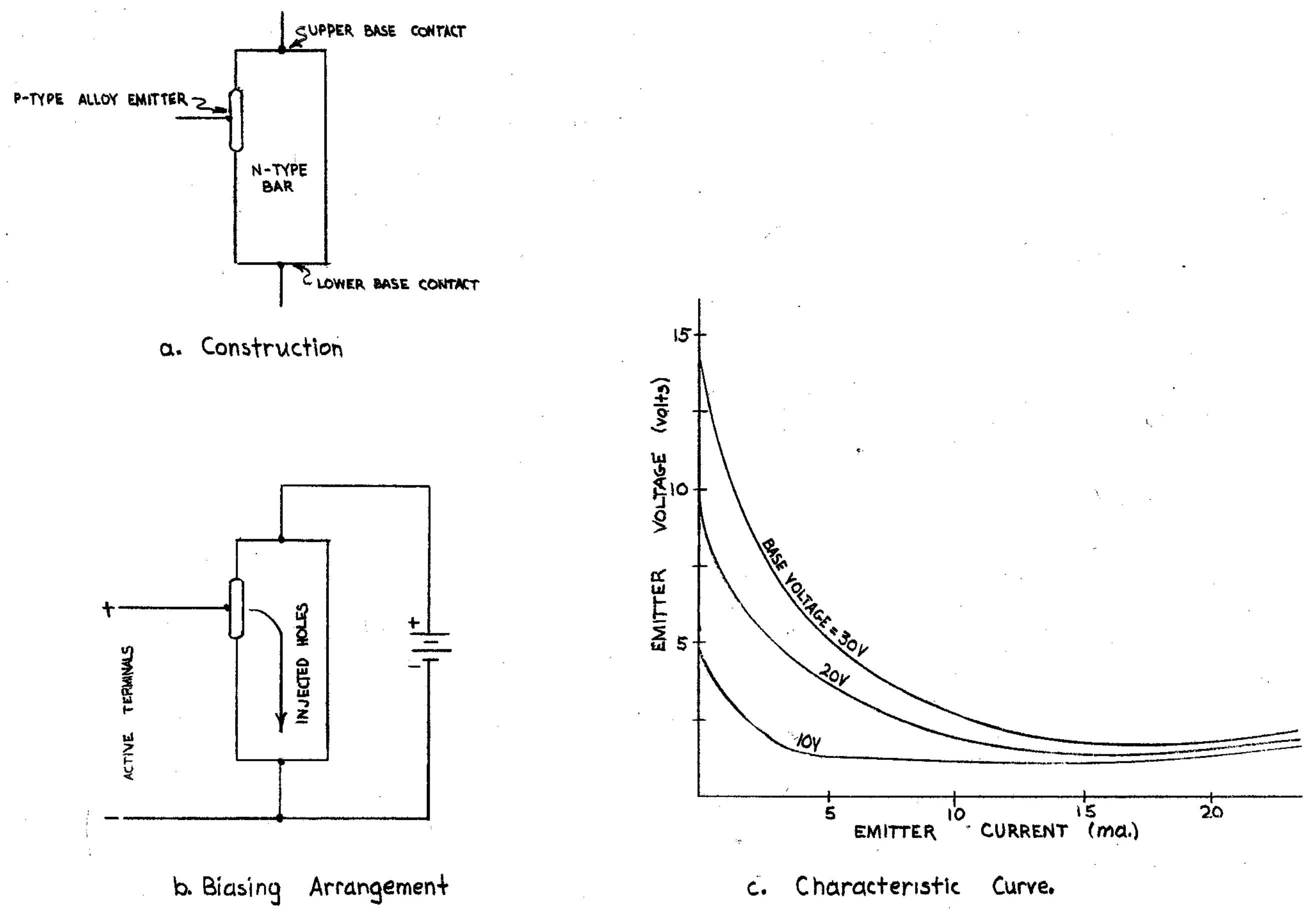


Figure 4.28. The Double Base Diode, Diagrams and Characteristics.

The electrical characteristic of the field effect transistor are shown in figure 4.27d. It can be seen that increasing the reverse bias on the gate will lower the drain current by decreasing the channel width.

At low drain voltages, the drain current increases linearly with voltage. This is to be expected because of the resistive nature of the bar. However, as the drain voltage increases, the drain current approaches a constant value. This happens because the voltage dropped in the channel will produce an additional reverse bias on the gate junction, decreasing the channel width. This action tends to keep the drain current constant. Since the channel becomes more positive toward the drain terminal, widening of the depletion region will take place near the drain, producing the distortion shown in figure 4.27c.

The electrical characteristic of the field effect transistor are similar to those of a vacuum tube. The input impedance is high (50,000-200,000 ohms) because the gate junction is reverse biased. Furthermore, the curves shown in figure 4.27d resemble those of a vacuum pentode.

The Double Base Diode. The double base diode is a regenerative switch that has found application in relaxation oscillator circuits. It is made by alloying a P-type emitter to a high resistivity N-type bar which has ohmic contacts attached to both ends. This configuration is shown in figure 4.28a.

In operation, a voltage is applied between the two base terminals, positive on the upper base as shown in figure 4.28b. This voltage will be distributed evenly along the length of the bar, so that portion of the bar near the emitter junction will be at some voltage less than the upper base voltage. Therefore, when the active terminals are shorted together (emitter to lower base), the emitter junction will be reverse biased. If now a positive voltage is applied to the emitter, the reverse bias will be reduced; and if the emitter voltage becomes greater than the voltage on the bar near the junction, the emitter will become forward biased and inject holes into the bar. These holes will be swept toward the lower base by the interbase electric field, lowering the resistivity in the region below the emitter. When this happens, the voltage distribution along the bar is altered, the lower portion of the bar becoming less positive because of its reduced resistance. Hence, the forward bias on the emitter is increased; and more carriers are injected. This regenerative action continues so the current will increase until the emitter voltage drops to a low value. This produces the negative resistance emitter characteristics shown in figure 4.28c.

If the emitter voltage is reduced while the device is in the on state, the number of injected carriers will decrease; and the resistance of the region below the emitter will increase. This will decrease the forward bias on the emitter so another regenerative cycle will begin, and the device will turn off.