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SUBJECT: TRANSISTOR CIRCUITS COURSE
NUMBER 1. INTRODUCTION

To: Distribution List

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Approved: DRB
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Abstract: This is the first in a series of notes covering material presented in lectures on transistor circuits for engineers. The introductory material below contains fundamental ideas about semiconductors which should be known by the transistor circuit designer. These ideas are presented in a simplified form but will serve as a basis for some future discussions later on.

The transistor is a solid state device, making use of a semiconductor as a medium for transporting charge, which is capable of producing a power gain. The properties of semiconductors make possible the control of a large current passing through one pair of electrodes of the transistor by means of a small current through a second pair of electrodes. This first note will discuss briefly the more important properties of semiconductors for transistor applications.

Metals, Semiconductors, Insulators

A metal is a solid in which the electric field $\underline{E}$ is everywhere zero, i.e., it is a body in which no space charge can exist. The resistivity of a metal is extremely low; copper, for example, having a resistivity of about 1.7×10^{-6} ohm-cm. Insulators, however, will support a space charge and are characterized by very high resistivity, of the order of 10^{15} ohm-cm.

Semiconductors fall in a class between these two extremes. They can contain a limited space charge and in a pure state, where they are called intrinsic semiconductors, may have resistivities of a few ohm-cm to several thousand ohm-cm at room temperature. For example, intrinsic germanium is about 60 ohm-cm and intrinsic silicon is about 60,000 ohm-cm at 25°C.

Another way of illustrating the difference between metals and semiconductors is to consider the number of conduction electrons. In

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metals this is about 10^{22} electrons per cc. Semiconductors range from 10^{11} to 10^{17} conduction electrons per cc, or one for every 10^5 to 10^{11} electrons in a metal.

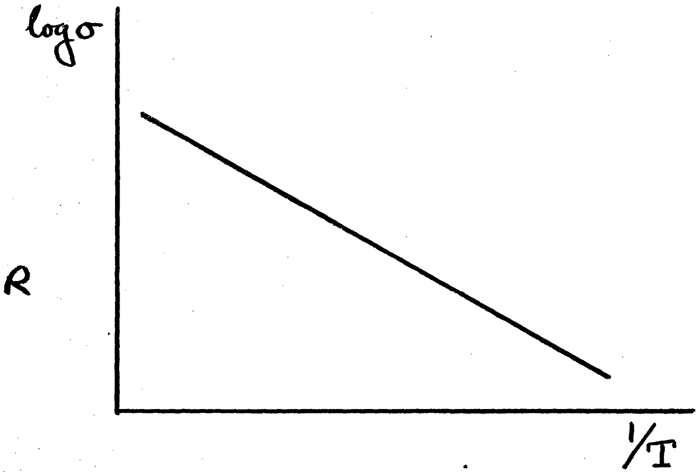
Impurity Semiconductors

Most semiconducting materials are not pure or intrinsic. Small amounts of impurities added to a semiconducting material will considerably reduce the resistivity. Therefore, the resistivity of a given sample can be controlled by its purity. The amount of impurity necessary to produce material useful for transistors is of the order of 10^{15} impurity atoms per cc whereas the normal population of semiconductor atoms is about 10^{22} per cc. That is, we are dealing with impurities of 1 part in 10 million.

Temperature and Conductivity

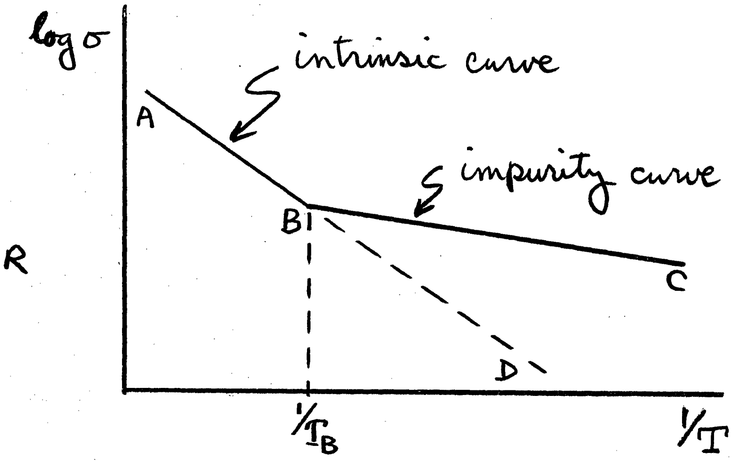
The relation between temperature and conductivity for an intrinsic semiconductor is shown below in Fig. 1.

FIG. 1
INTRINSIC
SEMICONDUCTOR



The conductivity σ increases with the absolute temperature T. If impurities are added to the semiconductor the conductivity is increased and the variation with temperature is as shown in Fig. 2.

FIG. 2
IMPURITY
SEMICONDUCTOR



In the interval BC the impurities control the value of the conductivity. However, above the temperature T_B the impurities no longer have any effect and the material behaves like an intrinsic semiconductor with the curve ABD. Since transistors depend on the properties of impurity semiconductors, this temperature T_B would represent the point where no transistor action could take place and, therefore, an absolute temperature limit for the device. In actual practice circuit failure would probably occur considerably below this temperature.

Crystalline Structure

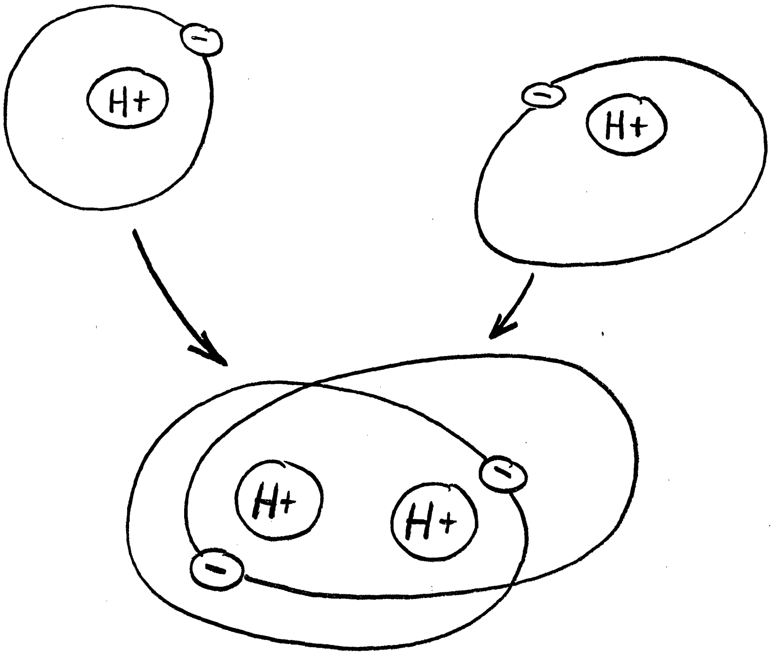
The atoms in a semiconductor form a crystalline structure, i.e., they arrange themselves in a regular pattern throughout the material. Moreover, the atoms in which we are interested are all members of the 4th column of the periodic table which is reproduced in part below in Fig. 3. The numbers in each column represent the positive charge on the nucleus of the atom.

FIG. 3

P-Type III		IV		N-Type VI	
B	+5	C	+6	N	+7
Al	+13	Ge	+14	P	+15
Ga	+31	Si	+32	As	+33
In	+49	Sn	+50	Sb	+51
Tl	+81	Pb	+82	Bi	+83

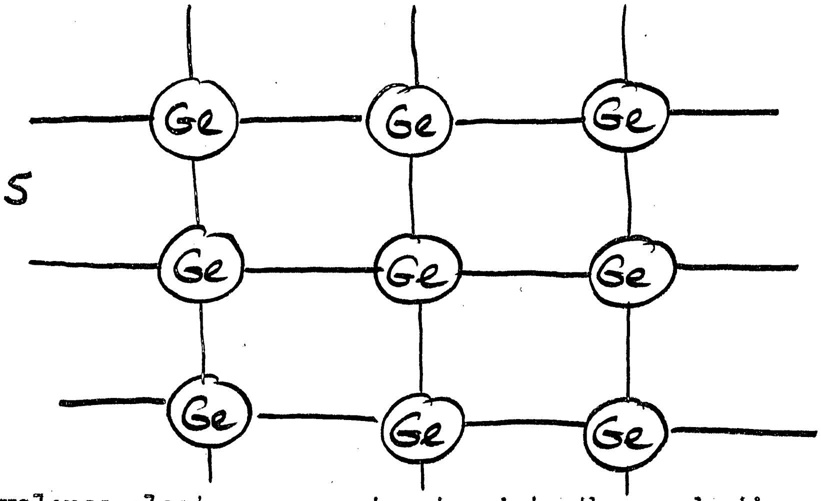
The 4th-column atoms all have four valence electrons and form valence crystals which are held together by electron-pair binding, i.e., pairs of electrons from different atoms form bonds which hold the crystal together. It is not within the scope of this paper to go into the details of atomic bonds but the sketch below may help to convey the idea.

FIG. 4



Two hydrogen atoms with single valence electrons are shown coming together to form an H_2 molecule which has electrons associated with both atoms. The "dual ownership" of the electrons by the two atoms serves to bind the molecule together. This can be represented by the symbol Ⓗ—Ⓗ In a similar manner a germanium crystal can be represented by:

FIG. 5

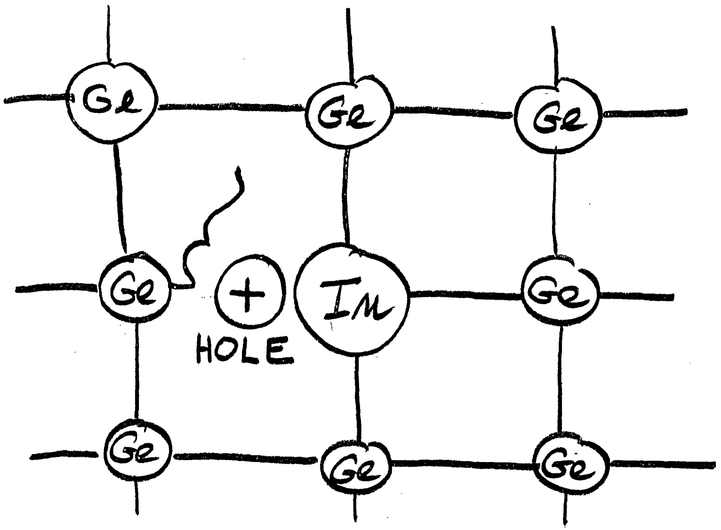


These valence electrons cannot enter into the conduction process since they are not free to move about.

Donors and Acceptors

If we now replace one of the germanium atoms in Fig. 5 by an impurity atom from the 3rd column of the periodic table in Fig. 3 the crystal will appear as follows:

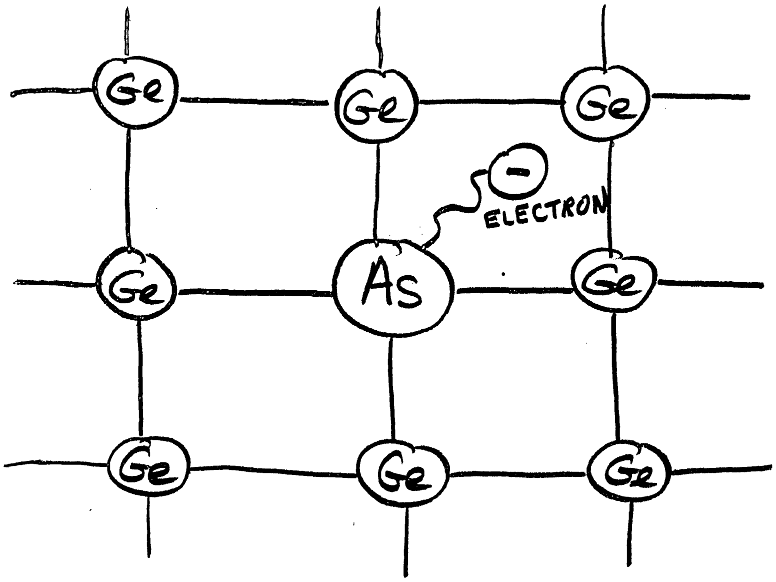
FIG. 6



Since the indium atom has only three valence electrons one bond will be incomplete leaving a hole in the crystal. As other valence electrons can now move in to fill this gap the hole effectively moves through the crystal and acts like a positive charge which can conduct current. Impurities of this type are called acceptors since they can accept valence electrons and the resulting impurity semiconductor is called a P-type semiconductor since the charge carriers are positive holes.

If a germanium atom is replaced by an element in column VI the situation is as follows:

FIG. 7



An extra electron is now available which is free to conduct current. An impurity of this type is called a donor since it provides conduction electrons, and the impurity semiconductor is called an N-type semiconductor since the charge carriers are negative electrons.

The two types of charge carriers mentioned above, holes and electrons, are important in transistors. Electrons have a mobility, $\mu = v/E$, of 3600 cm^2/volt-sec while holes have a mobility of 1700 cm^2/volt-sec. These mobility figures indicate the velocity of the carrier under a field of 1 volt/cm. However the base region in a transistor is traversed by carrier diffusion rather than acceleration by an electric field. The diffusion rate is directly related to the mobility, the diffusion constant being

$$D = \frac{1}{40} \mu \ cm^2/sec.$$

Therefore electrons will move through the transistor at a higher speed than will holes.

Operation of a pnp Transistor

Consider a transistor made up of N-type semiconducting material surrounded by P-type on either side. Three connections, emitter, base, and collector, are made to the three regions respectively as shown in Fig. 8.

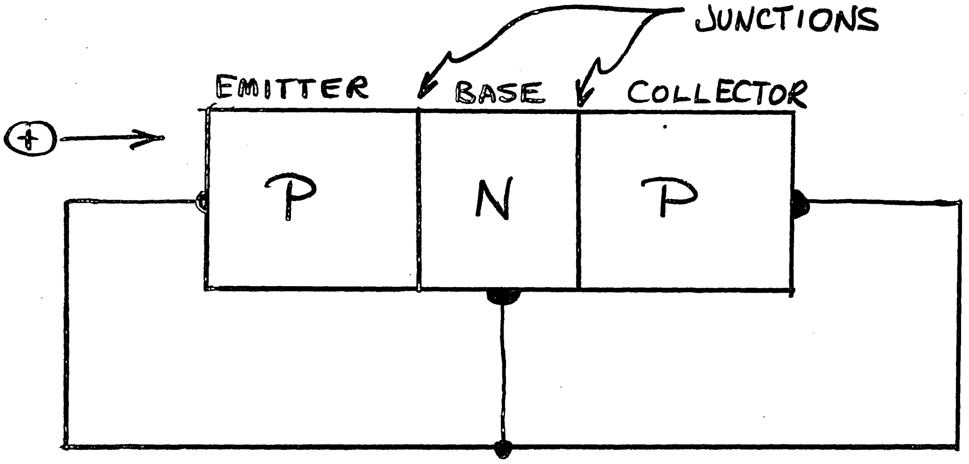
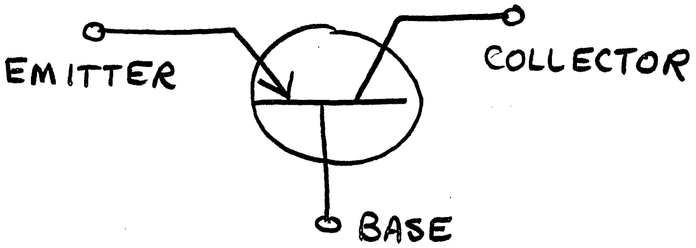


FIG. 8 A PNP JUNCTION TRANSISTOR

This is a pnp junction transistor and is represented schematically by

FIG. 9



If we consider the potential of a positive charge (or hole) passing from emitter to collector with all 3 elements grounded it will appear as shown in Fig. 10.

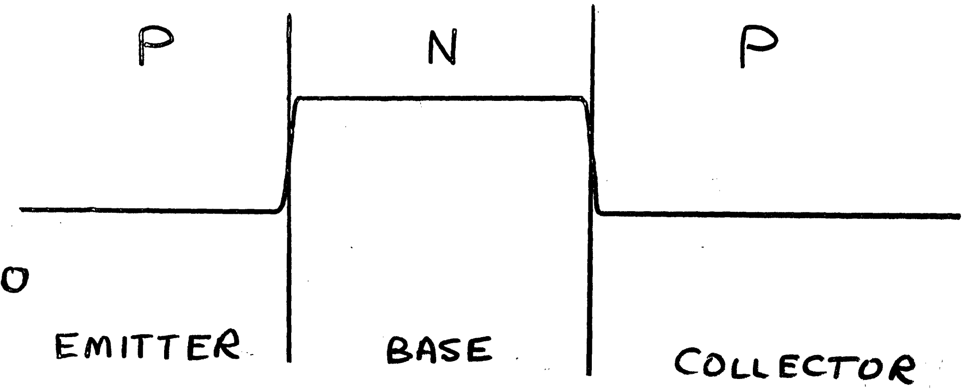
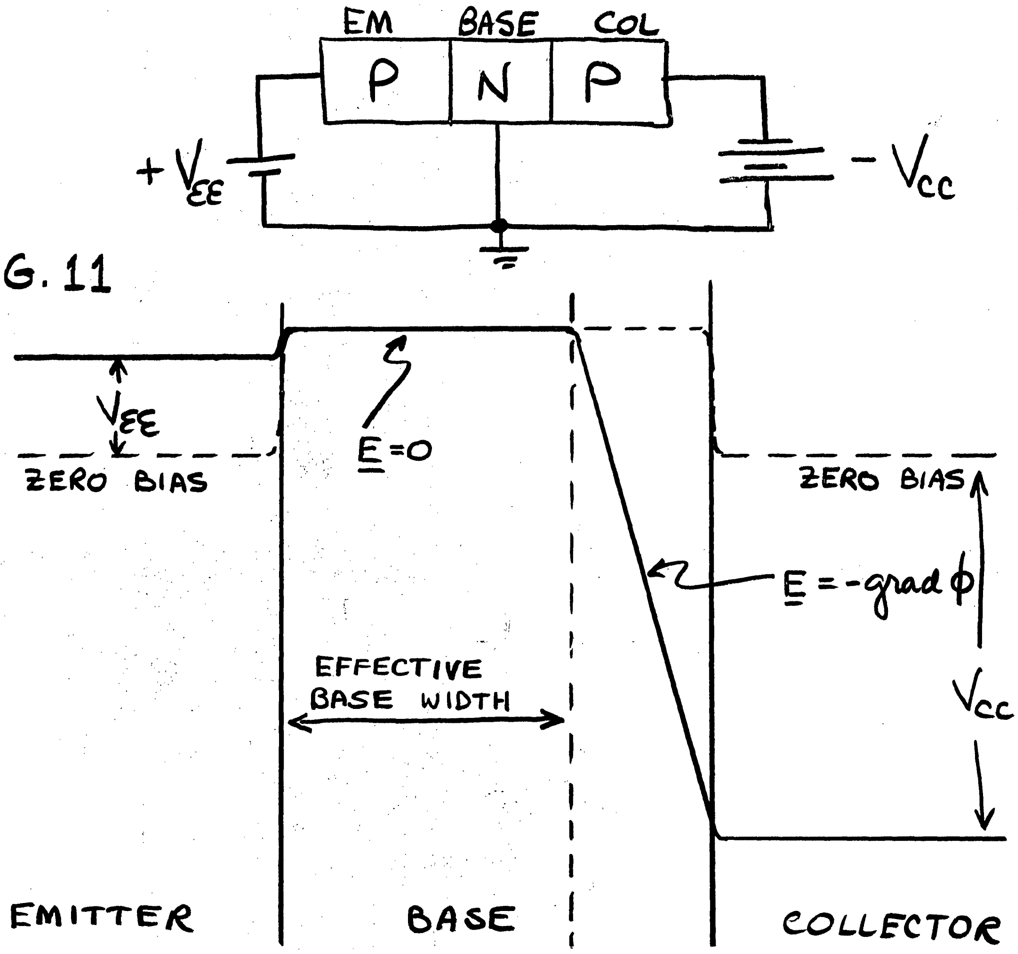


FIG. 10

When normal bias voltages are applied to the transistor as shown in Fig. 11 the potential diagram takes the form shown:

FIG. 11



Note particularly that there is no electric field through the largest part of the base region. Therefore, holes from the emitter must diffuse through the base until they reach the field in the collector region where they are accelerated into the collector.

Now consider a typical pnp which has a geometry as shown in Fig. 12. A hole leaving point A in the emitter under the influence of an emitter-base voltage moves through the base region by diffusion. The probability of its taking paths 1--6 to the collector is considerably greater than for path 7 into the base circuit. This is true for any hole leaving the emitter.

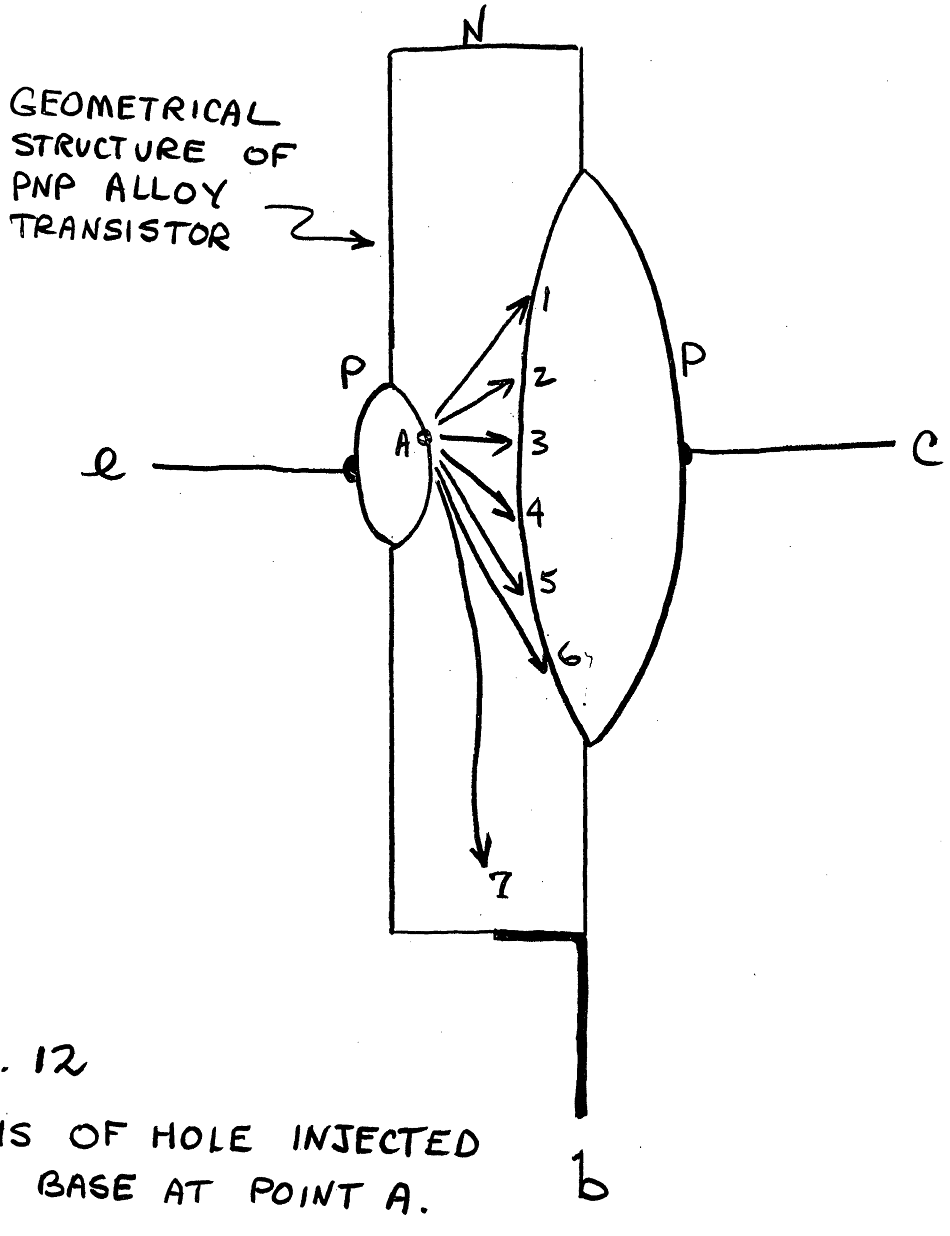


FIG. 12

PATHS OF HOLE INJECTED INTO BASE AT POINT A.

Therefore most holes will reach the electric field at the collector and be carried away into the collector. It is only when a very large current is flowing from emitter to collector that a reasonable number of holes can diffuse into the base -- say 2 percent or less of the total. Therefore, looking at the problem another way, if we require a certain current to flow in the base, we must have a much larger current flowing in the collector circuit. This is how we get a current gain in the transistor. A small base current will produce a large collector current.

This is, of course, an oversimplified picture but it does serve as an illustration of the transistor mechanism.

With the above introduction we will go into equivalent circuits in the second lecture.

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