25 YEARS OF SEMICONDUCTORS

PART 1 TRANSISTORS AND SMALL-SIGNAL DIODES

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THE FIRST transistor emerged from Bell Telephone Laboratories twenty-five years ago. Since then, the whole electronics industry has been transformed. Perhaps the most important change the transistor brought about was the introduction of new technologies of manufacture.

It is from the development of these technologies that the many types of present-day semiconductor device have come. These two articles present an overall, and necessarily brief, survey of these devices.

THE FIRST TRANSISTORS

In 1948 John Bardeen and Walter Brattain of Bell Telephone Laboratories invented the point-contact transistor.

The point-contact transistor had two fine wires placed close together on a semiconductor wafer. It was shown that not only was the current flowing between one of the wires and the semiconductor wafer affected by the current between the other wire and the wafer, but under certain conditions amplification could be obtained.

Perhaps the most important result of the point-contact transistor was that it provided experimental verification of the previous theoretical work. It paved the way for the junction transistor, a much more practicable device, invented by William Shockley also of Bell Telephone Laboratories in 1950.

JUNCTION TRANSISTOR

The junction transistor is essentially a sandwich of *p*-type and *n*-type semiconductor material containing two *pn* junctions. The first transistors were literally sandwiches, being made by the alloy-junction method.

A simplified cross-section of an alloy-junction transistor is shown in Fig. 1. This method of manufacture is still used for some audio-frequency transistors today.

Restrictions in minimum base width achievable with this technology gave the early alloy-junction transistors a cut-off frequency of approximately 1MHz, although refinements of the manufacturing technique raised this to approximately 5MHz.

ALLOY-DIFFUSED AND MESA TRANSISTORS

Other types of transistor were developed during the 1950's to overcome the limitations of the alloy-junction type. One of these types was the alloy-diffused transistor. The base layer of the alloy-diffused transistor was very thin, giving a cut-off frequency of approximately 800MHz.

Another type of transistor was the mesa transistor, originally developed to improve the switching characteristics. Its construction is shown in Fig. 2. The mesa transistor could operate with switching waveforms with rise times in the region of 1μs.

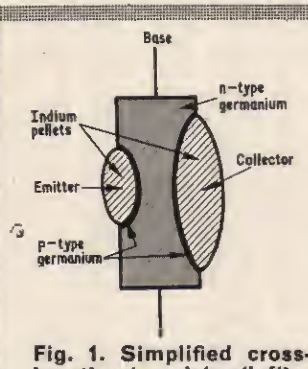
The technique of mesa etching is still used today in some types of transistor.

PLANAR TRANSISTORS

The introduction of the planar transistor in 1960 marked several important changes in transistor manufacture. Silicon rather than germanium was used as the semiconductor material with considerable advantages. Silicon transistors will withstand higher junction temperatures than germanium ones, and have higher voltage ratings and lower leakage currents.

Diffusion from vapour into clearly-defined areas of the silicon wafer enabled close control to be exercised, and the diffusion areas could be constructed by photographic techniques. For the first time in transistor manufacture, true mass-production techniques could be applied, with a consequent drop in price.

In the manufacture of silicon transistors an oxide layer is grown over a wafer of *n*-type silicon. Windows can be cut in this oxide by etching in areas defined by exposure through a mask, and *p*-type silicon formed by a boron diffusion. A second oxide layer is formed, selectively etched, and *n*-type silicon formed by a phosphorus diffusion. In this way a transistor is built up, as shown in Fig. 3.



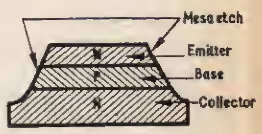


Fig. 1. Simplified cross-section of an alloy-junction transistor (left)

Fig. 2. Cross-section of mesa transistor (right)

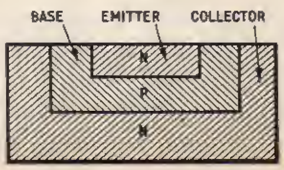


Fig. 3. Cross-section of planar transistor

Because the area of diffusion defined by a mask is the same for each transistor, the whole of a silicon wafer can be exposed at the same time. Thus up to 10,000 transistors can be manufactured on a silicon wafer 5cm in diameter in one manufacturing sequence.

Planar transistors can operate at frequencies up to the microwave region, well above 1GHz.

PLANAR EPITAXIAL TRANSISTORS

A development of the planar transistor that improves the performance is the planar epitaxial transistor. In this type, the transistor is formed in an epitaxial layer which is simply a layer of silicon with a near-perfect crystal structure. The silicon wafer on which the layer is grown forms a substrate as shown in Fig. 4.

By forming the epitaxial layer of high resistivity material but making the collector in the layer very thin, a transistor with high breakdown voltage and high collector current can be obtained.

FIELD-EFFECT TRANSISTORS

The transistors described so far are bipolar types, the current being conducted by two types of carriers (electrons and holes). The field-effect transistor (f.e.t.) is a unipolar transistor, the current being conducted by one type of carrier only.

A current-carrying channel of *n*-type silicon is surrounded by the *p*-type gate, as shown in Fig. 5. When a positive voltage is applied between drain and source, a current flows through the channel. A depletion layer is formed at the *p-n* junction of the gate and channel, and by applying a negative bias between the gate and source the depletion layer moves into the channel to restrict the area available for current flow. As the bias increases, a value is reached, the pinch-off voltage, at which no current flows. Thus the current through the f.e.t. can be controlled by the gate voltage, as in a triode valve.

The f.e.t. described is a junction f.e.t. or j.f.e.t. Another type can be constructed, the insulated-gate f.e.t., MOSFET or MOST. The initials MOS strictly speaking stand for Metal Oxide Semiconductor.

MOS refers to the construction of the transistor formed, a metal gate (aluminium or polysilicon) insulated from the silicon substrate by a layer of silicon oxide, as shown in Fig. 6.

By applying a voltage of the correct polarity to the gate, a current-carrying channel can be formed between the source and the drain, and when a voltage is applied across the source and the drain, a current flows.

The current-carrying channel in a *p*-type substrate is an *n*-type inversion layer. Similarly, a *p*-channel is formed in an *n*-type substrate. In addition, the *p*-channel and *n*-channels MOSTs can be enhancement or depletion types. Enhancement MOSTs are normally off, and require a gate voltage greater than the threshold voltage before conduction can occur. Depletion MOSTs are normally on, and require a pinch-off voltage on the gate to stop conduction.

Thus the circuit designer has four types of MOST to choose from for his application. All types of f.e.t. have very high input impedances, and so form a useful complement to bipolar transistors.

UNIJUNCTION TRANSISTOR

A unijunction transistor consists of a bar-shaped silicon slice with contacts either end and a *p-n* junction (the emitter) at some point along the length, see Fig. 7. It is therefore a three-terminal device but with only one junction.

With no emitter current flowing, the bar acts as a simple voltage divider with a fraction of the interbase voltage providing a reverse bias across the emitter junction. As the emitter voltage is increased, no appreciable current flows until the emitter voltage is greater than the reverse bias when there is a sudden increase in current. The unijunction transistor can therefore be used as a voltage-triggered device, in oscillators and sensors.

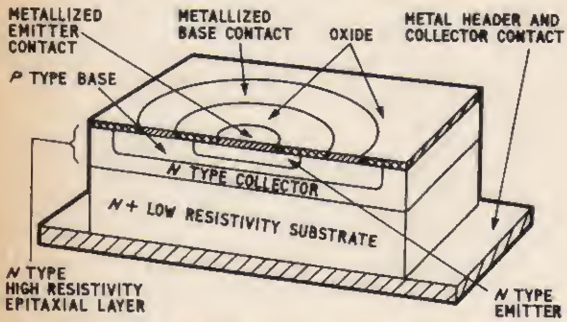


Fig. 4. Cross-section of planar epitaxial transistor

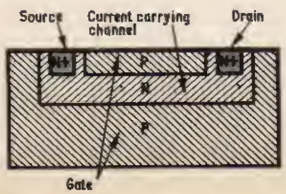


Fig. 5. Structure of junction FET

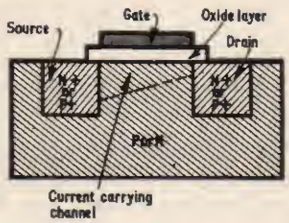


Fig. 6. Structure of MOSFET

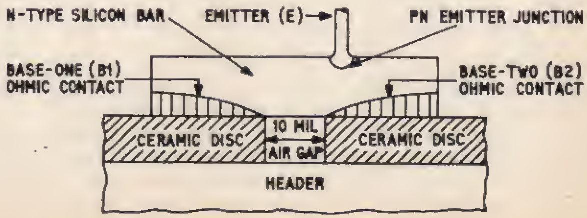


Fig. 7. Cross-section of a typical unijunction transistor

HIGHER POWER, HIGHER FREQUENCY

The development of the planar technology during the 1960's enabled the operating frequency of small-signal transistors to be raised so that by the end of the decade transistors with cut-off frequencies of 6GHz and capable of switching waveforms with rise times of 1ns were available.

Germanium power transistors could handle about 10W with a suitable heatsink. This power level was increased with the introduction of silicon power transistors. Today, silicon power transistors for low-frequency operation are manufactured by the single-diffused method, or, where high voltages are to be encountered (1kV or more), by the triple-diffused method. Powers of up to 150W typically can be handled.

The planar epitaxial technology enabled the operating frequency of power transistors to be raised considerably. More complex base-emitter configurations were developed to take operation high into the radio frequencies. A typical configuration is the interdigital one where fingers of the emitter layer interleave fingers of the base layer. Typical performance figures of present-day r.f. power transistors are 100W at 50MHz and 10W at 2GHz.

OTHER TYPES OF TRANSISTOR

The mexa transistor has an epitaxial base layer. The lightly-doped base is grown on a heavily-doped collector, the emitter layer diffused, and the complete structure mesa etched. The resulting transistor is rugged and has a low collector resistance.

Hometaxial transistors are made by simultaneously diffusing impurities on both sides of a homogeneous base layer, followed by a mesa etch of the emitter. Because of the homogeneous base, the risk of hot spots is reduced, and the transistor has good second-breakdown properties. The wide base width also gives good voltage breakdown properties.

Triple-diffused transistors are also manufactured in this way; the base and emitter are diffused on one side of the collector wafer as usual, but a third diffusion is used to form another collector layer. The technique can be used on planar or non-planar devices, and gives an improved value of collector saturation voltage.

SMALL-SIGNAL DIODES

The modern point-contact diode uses a germanium wafer to which a fine wire contact is welded. Because the current rating is very low (only a few milliamps) these diodes are only used for applications where junction diodes cannot be used efficiently, for example, as detector and mixer diodes at microwave frequencies.

Besides the low current rating, germanium point-contact diodes have a low inverse voltage and a high reverse current. These disadvantages were overcome by the introduction of the silicon junction diode in the mid-1950s. The junctions were made first by alloying with aluminium pellets, and later by diffusion. With the introduction of the planar technology, planar epitaxial diodes became available.

The limit of operating speed is set by the lifetime of the minority carriers formed by the reverse voltage. Gold doping reduces the lifetime of minority carriers in silicon, and by using silicon diodes with small junction areas and gold doping, recovery times of less than 5ns are obtained, making the diodes suitable for use in high speed computers.

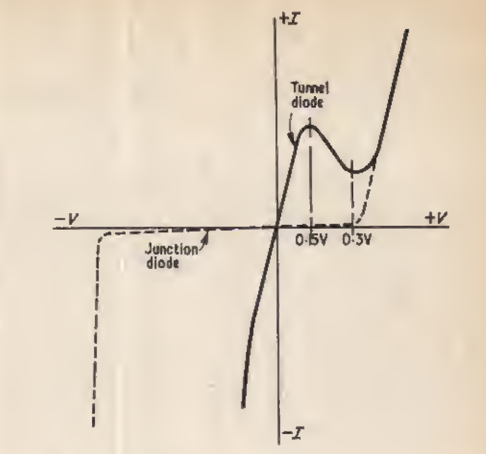


Fig. 8. Voltage/current characteristic of tunnel diode compared with junction diode

Faster switching diodes can be made by using gallium arsenide instead of silicon as the semiconductor material.

"ZENER" DIODES

As the reverse voltage across a junction diode is increased, a point is reached where the small leakage currently suddenly increases. This "breakdown" may be caused by electrons breaking from their bonds (the Zener effect), or more usually by avalanche breakdown.

In this type of breakdown, the electron minority carriers gain sufficient velocity to dislodge other electrons which in turn are accelerated sufficiently to dislodge further electrons. There is therefore a sudden build-up of current, and this may destroy the diode.

If the breakdown can be controlled, however, a useful range of devices, generally called (incorrectly) Zener diodes but more accurately voltage regulator diodes, is obtained. The value of breakdown voltage is determined by the doping level of the impurities in the diode.

Voltage regulator diodes are incorporated into supply lines to provide a simple method of stabilisation. Special types with very low temperature coefficients are called voltage reference diodes, and provide a simple form of voltage standard. If the voltage regulator diode is made rugged enough to withstand the dissipation, then it can be used to suppress voltage transient surges. Such range suppression diodes can withstand surges as high as 10kV provided the duration is only a few microseconds.

TUNNEL DIODES AND VARACTOR DIODES

Two types of diode use the properties of *pn* junctions to give special characteristics. The tunnel diode uses a normal *pn* junction in which both regions are heavily doped. With a reverse bias such a large number of electrons are present at the junction that some "tunnel" their way across the junction. Similarly, with a small forward bias below that required for conduction in a normal diode, tunnelling occurs. The forward tunnel current reaches a peak at approximately 0·15V, then decreases until normal forward conduction occurs at approximately 0·3V.

The V/I characteristic of a tunnel diode is shown by the full line in Fig. 8 with, for comparison, the characteristic of a normal diode in broken lines. The negative resistance part of the tunnel diode characteristic can be used in oscillators.

The varactor diode uses the capacitance of a reverse-biased *pn* junction. The reverse bias causes a depletion layer between the *p* and *n* regions, the width of the layer being proportional to the voltage. The junction area is made large to exploit this effect and to provide a reasonable change in capacitance with voltage.

Varactor diodes can be used as tuning elements to replace such devices as the parallel-plate tuning capacitor. They also have application as frequency multipliers. A string of varactor diodes and tuned circuits can be used to generate power efficiently at microwave frequencies from a lower-frequency source.

MICROWAVE DIODES

Some types of diode have properties that make them especially useful at microwave frequencies. Such types are the backward diode, PIN diode, Schottky barrier diode, and Gunn diode.

The backward diode, as the name implies, is a reverse-biased junction diode but one in which the breakdown voltage occurs very near the zero voltage point. Thus the resistance with reverse bias is lower than the forward resistance. Backward diodes can therefore be used as microwave detectors.

The PIN diode is also a *pn* junction but with a layer of intrinsic silicon between the *p* and *n* regions. With a forward bias, the PIN diode presents a low resistance because the bias injects carriers into the intrinsic region. With a reverse bias, however, the resistance remains very high. The PIN diode can therefore be used as a detector and also as a switch.

The Schottky barrier diode uses a metal-semiconductor junction as the rectifying element. Like the point-contact diode, the Schottky diode has the advantage of not suffering from minority carrier storage effects that limit the performance of junction diodes. Thus Schottky diodes can be used for higher-frequency applications, and also for very fast switching.

GUNN DIODE

The Gunn diode is not, strictly, a diode at all as it does not contain a rectifying element. It is formed by a thin layer of *n*-type gallium arsenide grown on a gallium arsenide substrate. The substrate forms the "anode" of the Gunn diode, while a "cathode" contact is formed on the face of the *n*-type layer.

When a low d.c. voltage is applied across the diode, high field regions called domains are formed at the cathode and rapidly cross to the anode. Current pulses are superimposed on the steady current through the diode, the frequency of the pulses depending on the transit time and therefore the thickness of the layer. For a thickness of 10μm, the frequency is 10GHz.

The Gunn diode can be mounted in a tuned cavity to form a simple microwave oscillator with advantages in space and cost over such devices as klystrons. Maximum output powers up to 3W can be obtained from Gunn diode oscillators.

The second article will describe power devices, photo devices, and integrated circuits.