A High-Frequency Diffused Base Germanium Transistor

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Techniques of impurity diffusion and alloying have been developed which make possible the construction of p-n-p junction transistors utilizing a diffused surface layer as a base region. An important feature is the high degree of dimensional control obtainable. Diffusion has the advantages of being able to produce uniform large area junctions which may be utilized in high power devices, and very thin surface layers which may be utilized in high-frequency devices.

Transistors have been made in germanium which typically have alphas of 0.98 and alpha-cutoff frequencies of 500 mc/s. The fabrication, electrical characterization, and design considerations of these transistors are discussed.

INTRODUCTION

Recent work [1, 2] concerning diffusion of impurities into germanium and silicon prompted the suggestion[3] that the dimensional control inherent in these processes be utilized to make high-frequency transistors.

One of the critical dimensions of junction transistors, which in many cases seriously restricts their upper frequency limit of operation, is the thickness of the base region. A considerable advance in transistor properties can be accomplished if it is possible to reduce this dimension one or two orders of magnitude. The diffusion constants of ordinary donors and acceptors in germanium are such that, with n realizable temperatures and times, the depth of diffused surface layers may be as small as 10^{-6} cm. Already in the present works layers slightly less than 1 micron (10^{-4} cm) thick have been made and utilized in transistors. Moreover, the times and temperatures required to produce 1 micron surface layers permit good control of the depth of penetration and the concentration of the diffusant in the surface layer with techniques described below.

If one considers making a transistor whose base region consists of such a diffused surface layer, several problems become immediately apparent:

(1) Control of body resistivity and lifetime during the diffusion heating cycle.

(2) Control of the surface concentration of the diffusant.

(3) Making an emitter on the surface of a thin diffused layer and controlling the depth of penetration.

(4) Making an ohmic base contact to the diffused surface layer.

One approach to the solution of these problems in germanium which has enabled us to make transistors with alpha-cutoff frequencies in excess of 500 mc/sec is described in the main body of the paper.

An important characteristic feature of the diffusion technique is that it produces an impurity gradient in the base region of the transistor. This impurity gradiant produces a "built-in" electric field in such a direction as to aid the transport of minority carriers from emitter to collector. Such a drift field may considerably enhance the frequency response of a transistor for given physical dimensions.[4]

The capabilities of these new techniques are only partially realized by their application to the making of high frequency transistors, and even in this field their potential has not been completely explored. For example, with these techniques applied to making a p-n-i-p structure the possibility of constructing transistor amplifiers with usable gain at frequencies in excess of 1,000 mc/sec now seems feasible.

DESCRIPTION OF TRANSISTOR FABRICATION AND PHYSICAL CHARACTERISTICS

As starting material for a p-n-p structure, p-type germanium of 0.8 ohm-cm resistivity was used. From the single crystal ingot rectangular bars were cut and then lapped and polished to the approximate dimensions: 200 × 60 × 15 mils. After a slight etch, the bars were washed in deionized water and placed in a vacuum oven for the diffusion of an n-type impurity into the surface. The vacuum oven consisted of a small molybdenum capsule heated by radiation from a tungsten coil and surrounded by suitable radiation shields made also of molybdenum. The capsule could be baked out at about 1,900°C in order that impurities detrimental to the electrical characteristics of the germanium be evaporated to sufficiently low levels.[5]

As a source of n-type impurity to be placed with the p-type bars in the molybdenum oven, arsenic doped germanium was used. The relatively high vapor pressure of the arsenic was reduced to a desirable range (about 10^{-4} mm of Hg) by diluting it in germanium. The use of germanium eliminated any additional problems of contamination by the dilutant, and provided a convenient means of determining the degree of dilution by a measurement of the conductivity. The arsenic concentrations used in the source crystal were typically of the order of 10^{17}–10^{19}/cc. These concentrations were rather high compared to the concentrations desired in the diffused surface layers since compensation had to be made for losses of arsenic due to the imperfect fit of the cover on the capsule and due to some chemical reaction and adsorption which occurred on the internal surfaces of the capsule.

The layers obtained after diffusion were then evaluated for sheet conductivity and thickness. To measure the sheet conductivity a four-point probe method[6] was used. An island of the surface layer was formed by masking and etching to reveal the junction between the surface layer and the p-type body. The island was then biased in the reverse direction with respect to the body thus effectively isolating it electrically during the measurement of its sheet conductivity. The thickness of the surface layer was obtained by first lapping at a small angle to the original surface (½°–1°) and locating the junction on the beveled surface with a thermal probe; then multiplying the tangent of the angle between the two surfaces by the distance from the edge of the bevel to the junction gives the desired thickness. Another particularly convenient method of measuring the thickness[7] is to place a half silvered mirror parallel to the original surface and count fringes, of the sodium *D*-line for example, from the edge of the bevel to the junction. Typically the transistors described here were prepared from diffused layers with a sheet conductivity of about 200 ohms/square, and a layer thickness of $(1.5 \pm 0.3) \times 10^{-4}$ cm.

When the surface layer had been evaluated, the emitter and base contacts were made using techniques of vacuum evaporation and alloying. For the emitter, a film of aluminum approximately 1,000 Å thick was evaporated onto the surface through a mask which defined an emitter area of 1 × 2 mils. The bar with the evaporated aluminum was then placed on a strip heater in a hydrogen atmosphere and momentarily brought up to a temperature sufficient to alloy the aluminum. The emitter having been thus formed, the bar was again placed in the masking jig and a film of gold-antimony alloy from 3,000 to 4,000 Å thick was evaporated onto the surface. This film was identical in area to the emitter, and was placed parallel to and 0.5 to 1 mil away from the emitter. The bar was again placed on the heater strip and heated to the gold-germanium eutectic temperature, thus forming the ohmic base contact. The masking jig was constructed to permit the simultaneous evaporation of eight pairs of contacts on each bar. Thus, using a 3-mil diamond saw, a bar could be cut into eight units.

Each unit, with an alloyed emitter and base contact, was then soldered to a platinum tab with indium, a sufficient quantity of indium being used to alloy through the n-type surface layer on the back of the unit. One of the last steps was to mask the emitter and base contacts with a 6- to 8-mil diameter dot of wax and form a small area collector junction by etching the unit attached to the platinum tab, in CP4. After washing in solvents to remove the wax, the unit was mounted in a header designed to allow electrolytically pointed wire contacts to be made to the base and emitter areas of the transistor. These spring contacts were made of 1-mil phosphor bronze wire.

ELECTRICAL CHARACTERIZATION

Of the parameters that characterize the performance of a transistor, one of the most important is the short circuit current gain (alpha) versus frequency. The measured variation of α and $\alpha/(1 - \alpha)$ (short-circuit current gain in the grounded emitter circuit) as a function of frequency for a typical unit is shown in Fig. 1. For comparison the same parameters for an exceptionally good unit are shown in Fig. 2.

In order that the alpha-cutoff frequency be a measure of the transit time of minority carriers through the active regions of the transistor, any resistance-capacity cutoffs, of the emitter and collector circuits, must lie considerably higher than the measured f_α. In the emitter circuit, an external contact resistance to the aluminum emitter of the order of 10

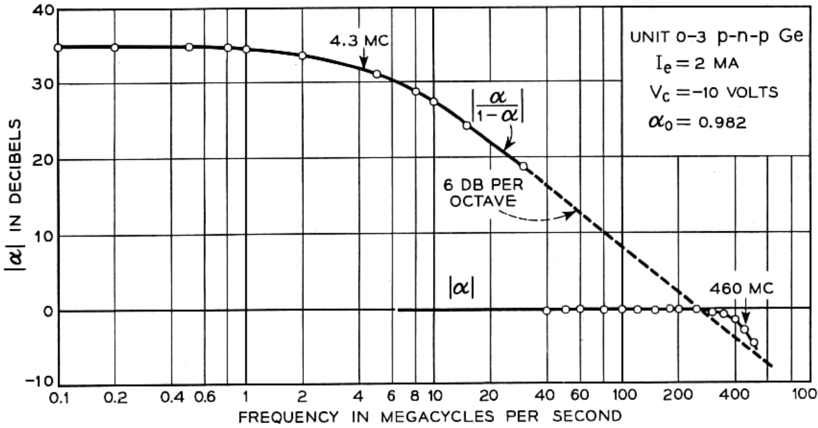

Fig. 1 — The grounded emitter and grounded base response versus frequency for a typical unit.

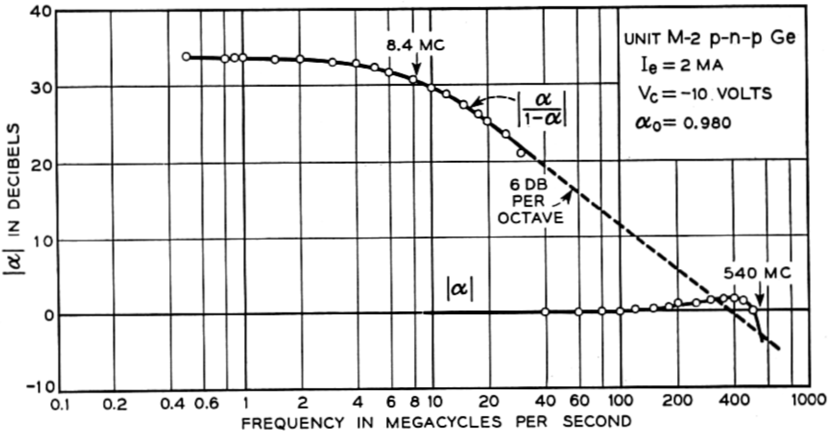

Fig. 2 — The grounded emitter and grounded base response versus frequency for an exceptionally good unit.

to 20 ohms and a junction transition capacity of 1 $\mu\mu$fd were measured. The displacement current which flows through this transition capacity reduces the emitter efficiency and must be kept small relative to the injected hole current. With 1 milliampere of current flowing through the emitter junction, and consequently an emitter resistance of 26 ohms, the emitter cutoff for this transistor was above 6,000 mc/sec. One can now see that the emitter area must be small and the current density high to attain a high emitter cutoff frequency. The fact that a low base resistance requires a high level of doping in the base region, and thus a high emitter transition capacity, restricts one to small areas and high current densities.

In the collector circuit capacities of 0.5 to 0.8 $\mu\mu$fd at a collector voltage of -10 volts were measured. There was a spreading resistance in the collector body of about 100 ohms which was the result of the small emitter area. The base resistance was approximately 100 ohms. If the phase shift and attenuation due to the transport of minority carriers through the base region were small at the collector cutoff frequency, the effective base resistance would be decreased by the factor $(1 - \alpha)$. The collector cutoff frequency is then given by

$$f_c = \frac{1}{2\pi C_c R_c}$$

where C_c = collector transition capacity

and R_c = collector body spreading resistance.

However, in the transistors described here the base region produces the major contribution to the observed alpha-cutoff frequency and it is more appropriate to use the expression

$$f_c = \frac{1}{2\pi C_c(r_b + R_c)}$$

where $r_b \equiv$ base resistance. This cutoff frequency could be raised by increasing the collector voltage, but the allowable power dissipation in the mounting determines an upper limit for this voltage. It should be noted that an increase in the doping of the collector material would raise the cutoff since the spreading resistance is inversely proportional to N_a, while the junction capacity for constant collector voltage is only proportional to $N_a^{1/2}$.

The low-frequency alpha of the transistor ranged from 0.95 to 0.99 with some exceptional units as high as 0.998. The factors to be considered here are the emitter efficiency γ and the transport factor β. The transport factor is dependent upon the lifetime in the base region, the recombination velocity at the surface immediately surrounding the emitter, and the geometry. The geometrical factor of the ratio of the emitter dimensions to the base layer thickness is >10, indicating that solutions for a planar geometry may be assumed.[8] If a lifetime in the base region of 1 microsecond and a surface recombination velocity of 2,000 cm/sec is assumed a perturbation calculation[9] gives

$$\beta = 0.995$$

The high value of β obtained with what is estimated to be a low base region lifetime and a high surface recombination velocity indicates that the observed low frequency alpha is most probably limited by the emitter injection efficiency. As for the emitter injection efficiency, within the accuracy to which the impurity concentrations in the emitter regrowth layer and the base region are known, together with the thicknesses of these two regions, the calculated efficiency is consistent with the experimentally observed values.

CONSIDERATIONS OF TRANSIT TIME

An examination of what agreement exists between the alpha-cutoff frequency and the physical measurements of the base region involves the mechanism of transport of minority carriers through the active regions of the transistor. The "active regions" include the space charge region of the collector junction. The transit time through this region[10] is no longer a negligible factor. A short calculation will show that with -10 volts on the collector junction, the space charger layer is about 4×10^{-4} cm thick and that the frequency cutoff associated with transport through this region is approximately 3,000 mc/sec.

The remaining problem is the transport of minority carriers through the base region. Depending upon the boundary conditions existing at the surface of the germanium during the diffusion process, considerable gradients of the impurity density in the surface layer are possible. However, the problem of what boundary conditions existed during the diffusion process employed in the fabrication of these transistors will not be discussed here because of the many uncertainties involved. Some qualitative idea is necessary though of how electric fields arising from impurity gradients may affect the frequency behavior of a transistor in the limit of low injection.

If one assumes a constant electric field as would result from an exponential impurity gradient in the base region of a transistor, then the continuity equation may be solved for the distribution of minority carriers.[4] From the hole distribution one can obtain an expression for the transport factor β and it has the form

$$\beta = e^{\eta} \frac{Z}{\eta \sinh Z + Z \cosh Z}$$

where

$$\eta \equiv \frac{1}{2} \ln \frac{N_e}{N_c} = \frac{1}{2} \frac{qE}{kT} w,$$

$$Z \equiv [i\varphi + \eta^2]^{1/2}$$

$$\varphi = \omega \frac{w^2}{D_p}$$

$N_e \equiv$ donor density in base region at emitter junction

$N_c \equiv$ donor density in base region at collector junction

$E \equiv$ electric field strength

$D_p \equiv$ diffusion constant for holes

$w \equiv$ width of the base layer

A plot of this function for various values of η is shown in Fig. 3. For $\eta = 0$, the above expression reduces to the well known case of a uniformly doped base region. The important feature to be noted in Fig. 3 is that relatively small gradients of the impurity distribution in the base layer can produce a considerable enhancement of the frequency response.

It is instructive to calculate what the alpha-cutoff frequency would be for a base region with a uniform distribution of impurity. The effective thickness of the base layer may be estimated by decreasing the measured thickness of the surface layer by the penetration of the space charge region of the collector and the depth of the alloyed emitter structure. Using a value for the diffusion constant of holes in the base region appropriate to a donor density of about 10^{17}/cc,

$$300 \text{ mc/s} \leqq f_\alpha \leqq 800 \text{ mc/s}$$

This result implies that the frequency enhancement due to "built-in" fields is at most a factor of two. In addition it was observed that the alpha-cutoff frequency was a function of the emitter current as shown in Fig. 4. This variation indicates that at least intermediate injection

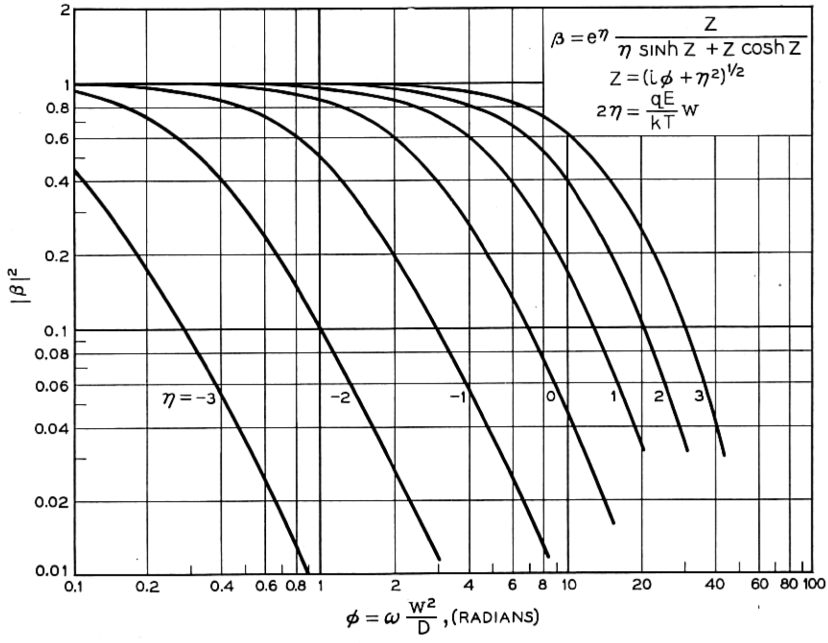

Fig. 3 — The variation of | β | versus frequency for various values of a uniform drift field in the base region.

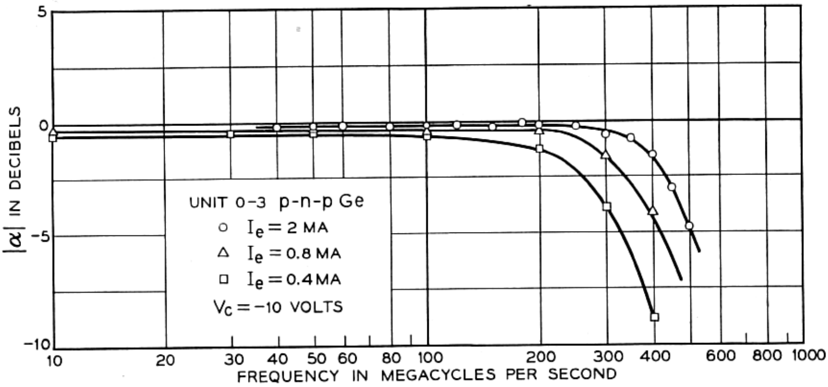

Fig. 4 — The variation of the alpha-cutoff frequency as a function of emitter current.

levels exist in the range of emitter current shown in Fig. 4. The conclusion to be drawn then is that electric fields produced by impurity gradients in the base region are not the dominant factor in the transport of minority carriers in these transistors.

The emitter current for a low level of injection could not be determined by measuring f_α versus I_e because the high input impedance at very low levels was shorted by the input capacity of the header and socket. Thus at very small emitter currents the measured cutoff frequency was due to an emitter cutoff and was roughly proportional to the emitter current. At $I_e \geqq 1$ ma this effect is small, but here at least intermediate levels of injection already exist.

A further attempt to measure the effect of any "built-in" fields by turning the transistor around and measuring the inverse alpha proved fruitless for two reasons. The unfavorable geometrical factor of a large collector area an a small emitter area as well as a poor injection efficiency gave an alpha of only

$$\alpha = 0.1$$

Secondly, the injection efficiency turns out in this case to be proportional to $\omega^{-1/2}$ giving a cutoff frequency of less than 1 mc/sec. The square-root dependence of the injection efficiency on frequency may be readily seen. The electron current injected into the collector body may be expressed as

$$J_e = qD_nN\left[\frac{1 + i\omega\tau_e}{L_e^2}\right]^{1/2}$$

where $q \equiv$ electronic charge

$D_n \equiv$ diffusion constant of electrons

$$N = \frac{q}{kT} v_1 n_c$$

$v_1 \equiv$ voltage across collector junction

$n_c \equiv$ density of electrons on the p-type side of the collector junction

$\tau_e \equiv$ lifetime of electrons in collector body

$L_e \equiv$ diffusion length of electrons in the collector body

Since the inverse cutoff frequency is well below that associated with the base region, we may regard the injected hole current as independent of the frequency in this region. The injection efficiency is low so that

$$\gamma \approx \frac{J_p}{J_e} \ll 1$$

Thus at a frequency where

$$\omega\tau_e \gg 1$$

then

$$\gamma \propto \omega^{-1/2}$$

An interesting feature of these transistors was the very high current densities at which the emitter could be operated without appreciable loss of injection efficiency. Fig. 5 shows the transmission of a 50 millimicrosecond pulse up to currents of 18 milliamperes which corresponds to a current density of 1800 amperes/cm^2. The injection efficiency should remain high as long as the electron density at the emitter edge of the base region remains small compared to the acceptor density in the emitter regrowth layer. When high injection levels are reached the injected hole density at the emitter greatly exceeds the donor density in the base region. In order to preserve charge neutrality then

$$p \approx n$$

where $p \equiv$ hole density

$n \equiv$ electron density

As the injected hole density is raised still further the electron density will eventually become comparable to the acceptor density in the emitter regrowth layer. The density of acceptors in the emitter regrowth

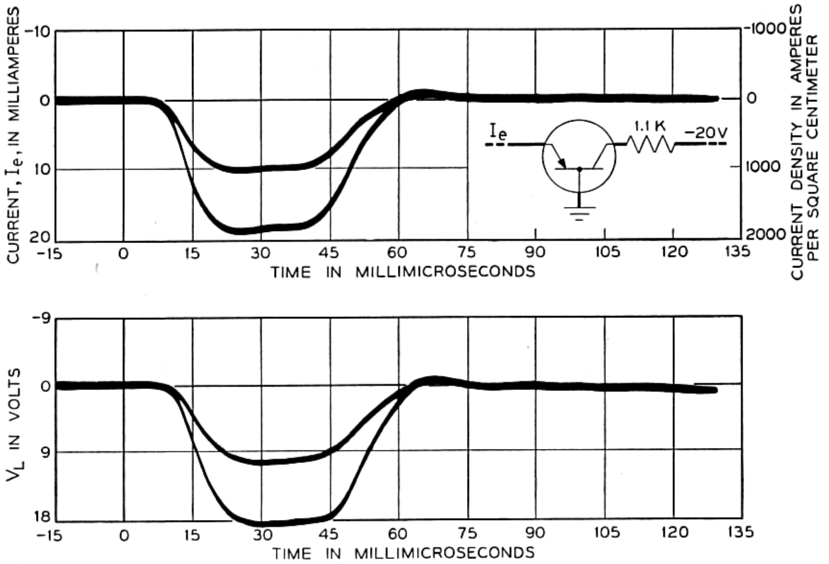

Fig. 5 — Transmission of a 50 millimicrosecond pulse at emitter currents up to 18 ma by a typical unit. (Courtesy of F. K. Bowers).

region is of the order of

$$N_A \approx 10^{20}/\text{cc}$$

and this is to be compared with injected hole density at the base region side of the emitter junction. The relation between the injected hole density and the current density may be approximated by[8]

$$J_p = \frac{2qD_p p_1}{w}$$

where p_1 = hole density at emitter side of base region

w = width of base region

A short calculation indicates that the emitter efficiency should remain high at a current density of an order of magnitude higher than 1,800 amp/cm^2. The measurements were not carried to higher current densities because the voltage drop across the spreading resistance in the collector was producing saturation of the collector junction.

CONCLUSIONS

Impurity diffusion is an extremely powerful tool for the fabrication of high frequency transistors. Moreover, of the 50-odd transistors which were made in the laboratory, the characteristics were remarkably uniform considering the variations usually encountered at such a stage of development. It appears that diffusion process is sufficiently controllable that the thickness of the base region can be reduced to half that of the units described here. Therefore, with no change in the other design parameters, outside of perhaps a different mounting, units with a 1000 mc/s cutoff frequency should be possible.

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