

June 4, 1957

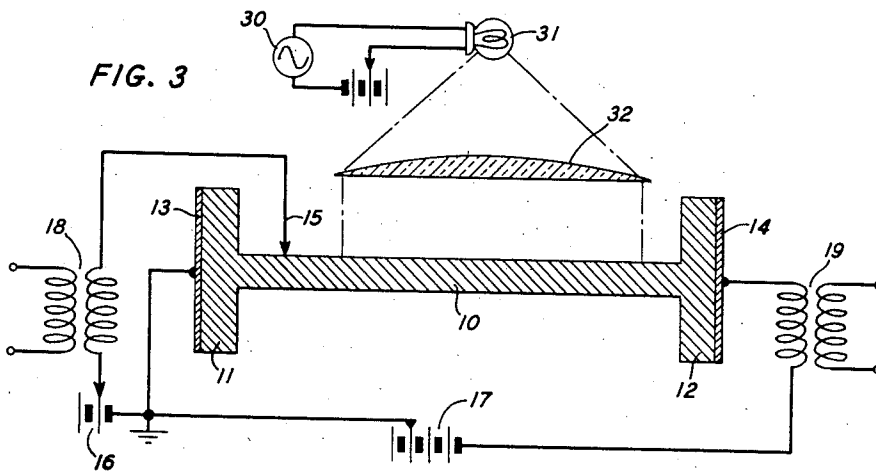
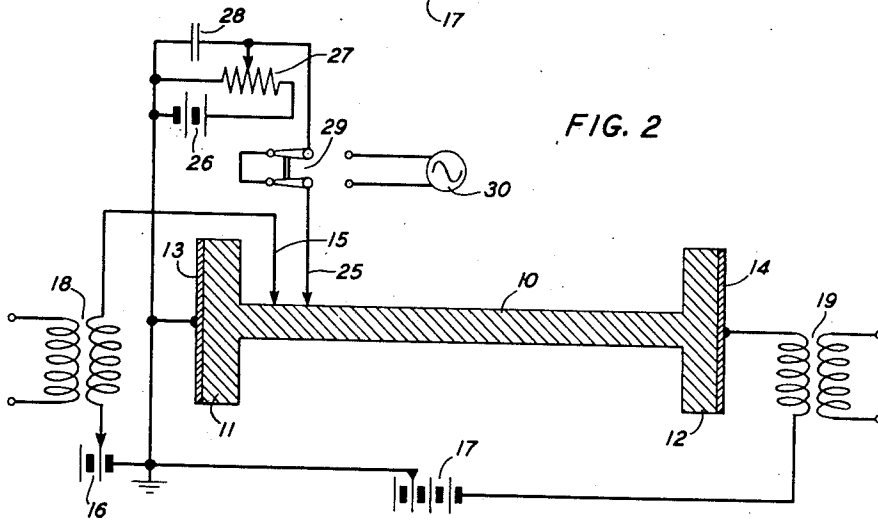
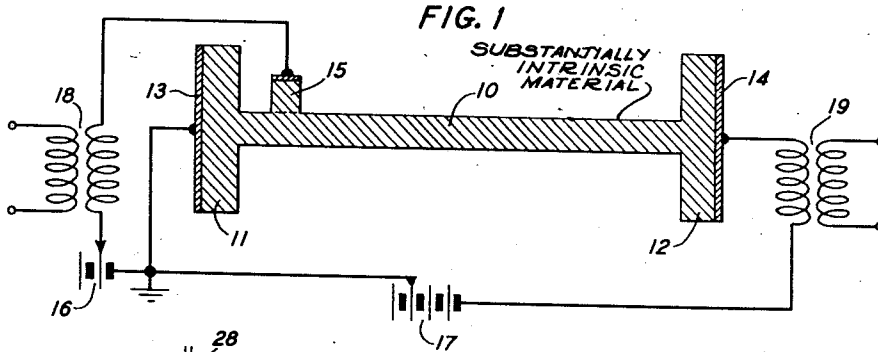
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2,794,863

SEMICONDUCTOR TRANSLATING DEVICE AND CIRCUIT

Filed July 20, 1951

2 Sheets-Sheet 1



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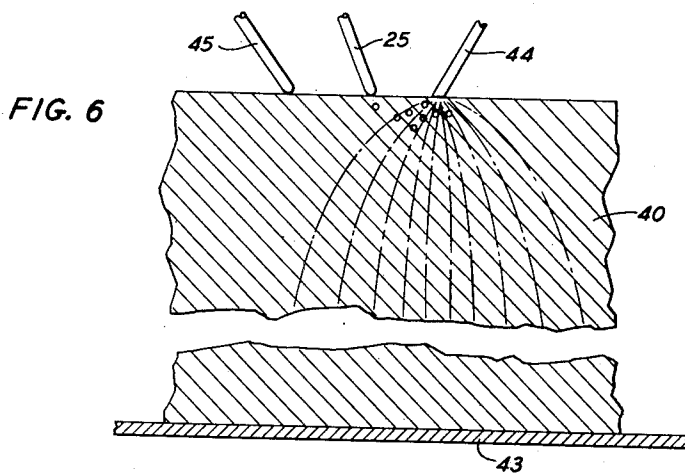
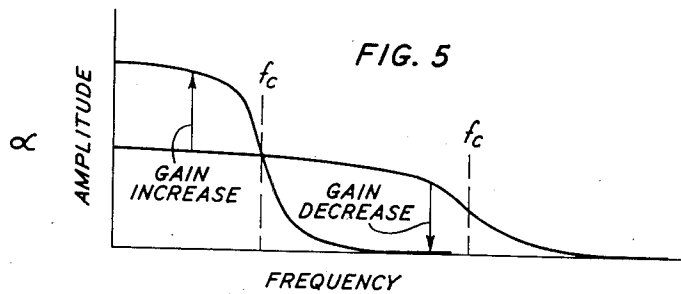
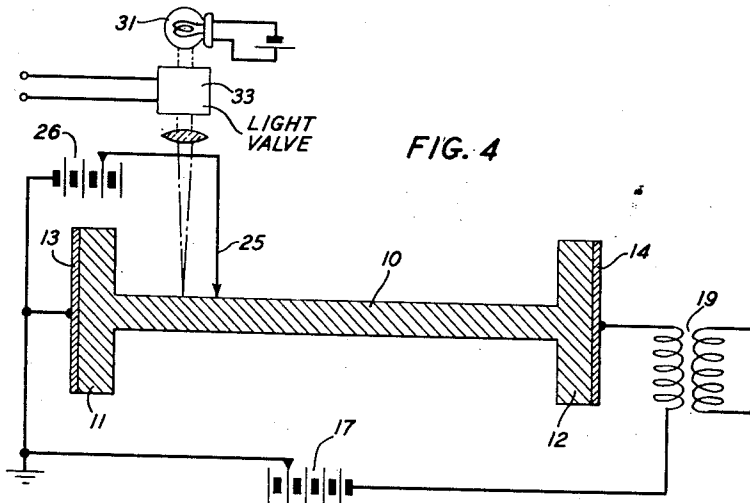
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2 Sheets-Sheet 2



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SEMICONDUCTOR TRANSLATING DEVICE AND CIRCUIT

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Application July 20, 1951, Serial No. 237,746

6 Claims. (Cl. 179—171)

This invention relates to electrical translating devices that make use of the electrical properties of semiconductive material.

Semiconductor translating devices of one well-known class comprise typically a body of an impurity-type semiconductive material such as germanium or silicon, a pair of electrodes in contact with the body and, connected to the electrodes, an external circuit that includes a current source. The mobile charge carriers provided by the material for the conduction of current through the body are very largely of one sign only, viz., positive charges or holes (in which case the material is said to exhibit extrinsic conductivity of p-type), or electrons in the conduction energy-band (in which case the material is said to exhibit extrinsic conductivity of n-type). Additional charge carriers, i. e., electrons and/or holes, are then produced in the body, e. g., by injection into the body from an emitter electrode, in varying amount controlled by the signal to be translated; and these additional carriers, by one mechanism or another, vary the internal impedance of the device to the flow of current through the external circuit. The current variations in the external circuit comprise an amplified replica of the signal. Such devices are useful as amplifiers, oscillators, modulators, photo-responsive devices, and otherwise.

In a particular type of translating device that is treated in Pearson et al. Patent 2,502,479 issued April 4, 1950, and in Bell System Technical Journal, vol. 28, July 1949, for example, the semiconductive body takes the form of a filament with base and collector electrodes in contact with the ends thereof and an emitter connected to the filament adjacent one of the end-electrodes. If the material comprising the filament is of n-type, the external circuit causes a steady flow of free electrons through the filament from the remote end-electrode to the end-electrode adjacent the emitter. A signal applied to the emitter results in the injection of holes into the filament, the concentration of injected holes at the emitter varying in conformity with the variations in amplitude of the signal. Under the influence of the unidirectional field that the external source establishes between the end-electrodes the injected holes drift toward the remote electrode. Simultaneously electrons are drawn into the filament from the remote electrode in correspondingly varying concentration to maintain the static charge constant. The presence of the carriers so introduced increases the conductivity of the material forming the filament and changes, or modulates it, at the frequency of the signal. This in turn results in substantial variations in the current flowing in the external circuit inasmuch as it is almost exclusively the resistance of the material that accounts for the total internal resistance between the end-electrodes.

It is to be noted that the variation or modulation of conductivity induced by the signal progresses through the filament at the velocity of drift fixed by the strength of the field between the end-electrodes. This finite velocity of transport of the conductivity modulation limits the rate at which the average conductivity of the filament

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can follow signal variations, and therefore establishes a limiting, or cut-off frequency for the device.

In contrast with all such prior art, the present invention contemplates a semiconductor translating device of the class described in which, under operating conditions, the semiconductive body, or a major portion of it, exhibits substantially intrinsic conductivity.

In one aspect the invention is featured by the environment, within a semiconductive body, in which charge carriers are produced under the control of a signal to be translated, that environment being characterized by substantial equality of the respective concentrations of holes and free electrons present in the body and by conductivity that is substantially proportional to the concentration of carriers of either sign.

In another aspect the invention is distinguished by the comparatively low velocity at which conductivity modulation due to signal-produced carriers is transported through the semiconductive body, and by correspondingly high current multiplication. One of the various forms in which the invention is susceptible of embodiment is closely related in superficial respects with the filamentary semiconductor device hereinbefore described and, in part because of this relation and in part because of its amenability to quantitative mathematical exposition, it is largely with reference to such an embodiment that the nature of the present invention and its various features, objects and advantages will be more fully developed hereinafter.

The filamentary transistor of the prior art to which reference has been made employs semiconductive material that has extrinsic conductivity, and its principle of operation has heretofore been understood to depend on the use of material of that character. Thus, the teaching, and observation, that the velocity of transport of the injected holes and of the resulting conductivity modulation is equal to the velocity of drift in the applied electric field, is associated with the fact that in extrinsic material the holes injected by the emitter do not appreciably modify the field associated with a given current density in the filament since substantially all of the carriers are the electrons normally present. Likewise associated with the assumption of extrinsic conductivity is the teaching and observation that the cut-off frequency is essentially proportional to the voltage across the end-electrodes, and that the largest possible zero-frequency current multiplication is $(b+1)$ where b is the ratio of electron mobility to hole mobility, or about 3.1 if the material of the filament is germanium.

I have discovered that conductivity modulation is possible also in material of intrinsic conductivity, and that a quite distinct gain mechanism operates in such case yielding results not obtainable otherwise. In a filamentary transistor embodying the invention, for example, the velocity of transport of the conductivity modulation is the diffusion velocity that is characteristic of the material and not the drift velocity fixed by the applied longitudinal electric field. Among the practical implication of this distinctive characteristic are a reduced cut-off frequency that is independent of the applied field, and greatly enhanced current multiplication, or gain, that can be adjusted by control of the applied field.

Ideally intrinsic semiconductive materials are not known. Such a material would contain free electrons and holes in exactly equal numbers at thermal equilibrium or, otherwise stated, the ratio P_0 of holes to free electrons would be exactly unity. In the case of an impurity semiconductor such as germanium or silicon this would require an exact balance or donor and acceptor impurities or a complete absence of significant impurities. In the n-type germanium commonly used for transistors and rectifiers the significant impurities are present as almost imperceptible traces but they nevertheless have a pro-

found effect on the characteristics of the material. The impurity concentration (excess of donors over acceptors) is reflected in the resistivity of the material, which ranges usually from about 1 to 20 ohm-centimeters at room temperature as compared with the approximately 60 ohm-centimeters resistivity that it is estimated pure germanium should have. The degree to which a semiconductor is extrinsic or intrinsic may be specified by the ratio P_0 of hole concentration to electron concentration at thermal equilibrium, that ratio being unity in the case of ideally intrinsic material as indicated hereinbefore. Typical values of P_0 for n-type germanium at room temperature are 0.0013 (for 2 ohm-centimeter material), 0.008 (for 5 ohm-centimeter), 0.030 (for 10 ohm-centimeter) and 0.100 (for 20 ohm-centimeter), from which it will be understood that the hole concentration can be regarded as negligibly small for most practical purposes. Although it is a matter of scientific observation that the value of P_0 varies toward unity with increase in temperature of the material, the present invention contemplates materials and circumstances such that the semiconductive body exhibits substantially intrinsic conductivity under practical operating conditions. Substantially intrinsic material is material in which the difference between the number of free holes and the number of free electrons present is less than the number of free hole-electron pairs. Such material exhibits properties which are substantially similar to those of ideally intrinsic material.

In accordance with a feature of the invention a semiconductor device depending upon conductivity modulation for its operation has provision, in the nature of conductivity biasing means, for producing holes and free electrons in equal numbers in the semiconductive body in such profusion as to reduce substantially any disparity in the respective concentrations of total holes and total free electrons.

A further and important feature of the invention is a conductivity biasing means that does not depend upon thermal excitation of additional carriers for its operation. The latter means, in certain embodiments, subjects the semiconductive body to energy rays, and more specifically to light rays, that are of such nature and intensity as to penetrate the body and liberate electron-hole pairs therein in the desired profusion. In other embodiments an emitter in contact with the semiconductive body is arranged to inject carriers of such sign and profusion as to substantially equalize the hole and electron concentrations prevailing in the body; and a separate emitter may be provided for the signal-controlled injection of carriers. In accordance with still another feature of the invention the signal-controlled emitter is spaced from the body portion over which the conductivity-biasing means is operative.

In the accompanying drawings:

Fig. 1 illustrates diagrammatically a filamentary transistor in accordance with the invention;

Fig. 2 illustrates a modification in which an auxiliary emitter and current source are provided for injecting carriers to equalize hole and electron concentrations;

Fig. 3 illustrates a further modification in which the filamentary body is illuminated so as effectively to increase P_0 ;

Fig. 4 illustrates a modification in which a signal-modulated light beam is used in lieu of a signal-controlled emitter;

Fig. 5 comprises curve diagrams; and

Fig. 6 illustrates an embodiment that makes use of the spreading resistance adjacent a collector electrode.

Referring to Fig. 1 there is shown a body of semiconductive material comprising a filament 10 with enlarged terminal portions 11 and 12 to which are attached, in low-resistance ohmic contact, a base electrode 13 and a collector electrode 14, respectively. Adjacent the base electrode and in contact with filament 10 is an emitter electrode 15. The foregoing elements may conform in

relative and absolute dimensions with those of the prior art filamentary transistor. The external circuit in Fig. 1 is of the grounded-base type, in which the signal input circuit extends from emitter to base and the signal output circuit extends from collector to base. The input circuit includes an emitter biasing battery 16, and the output circuit includes a collector biasing battery 17, both poled oppositely relative to the base as shown. Signals to be amplified may be introduced into the input circuit by means of an input transformer 18, if no direct-current signal component is to be transmitted, and amplified signals may be removed from the output circuit by an output transformer 19.

The foregoing paragraph is equally applicable to Figs. 2 and 3, and to Fig. 4 also, except for the references to emitter and input circuit.

The filament 10 in Fig. 1 may be understood as having substantially intrinsic conductivity uniformly throughout its length. In such case, as in other embodiments disclosed herein, the body portion of substantially intrinsic conductivity is of such extent and location that its body resistance accounts for at least the major part of the resistance internally of the collector circuit, i. e., of the resistance of the body between base and collector connections. The signal emitter 15 may advantageously comprise a stub, integral with filament 10, of the same material as the filament (that is, germanium or silicon, e. g.) but of strongly extrinsic conductivity adapted to inject carriers of the desired sign in the manner of a p-n junction. Assuming henceforward that it is holes that are to be injected by the signal emitter, the latter may comprise, specifically, a stub of material the conductivity of which is strongly p-type and high compared to that of the filament.

The collector circuit battery 17 establishes a longitudinal "sweeping" field in filament 10 that drives a steady current through the filament from base to collector. That current comprises holes and electrons in substantially equal proportions, flowing at drift velocity in respectively opposite directions. Biasing battery 16 fixes emitter 15 at a potential slightly greater than that of the contiguous portion of filament such that carriers are injected into the filament, and under the conditions assumed the injected carriers will consist essentially of holes. Superposed on the bias voltage in the emitter circuit is the signal voltage, and as the latter varies in instantaneous amplitude it produces corresponding variations in the injection of carriers from the emitter. The injected holes flow through the filament to the collector and to the external collector circuit where they contribute directly to the output current in proportion to the instantaneous amplitude of the signal prevailing during their injection. It will be understood that if the signal amplitude varies slowly enough the hole concentration at any moment throughout the filament will be substantially uniform, although varying from moment to moment as the signal does. In addition to the direct contribution of the injected holes to the signal output current, the presence of the holes in the filament alters the conductivity of the filament and therefore also the resistance offered to the flow of current from collector circuit battery 17. This conductivity modulation of the filament can and does make a relatively great contribution to the signal output current and accounts largely for the "current multiplication" or gain of the device. Further significant details of the construction and operation will appear hereinafter.

Material suitable for the purposes of the present invention can be prepared by progressive removal of significant impurities. It is known that in casting an ingot of germanium, for example, solidification of the material progressively from one end of the ingot tends to cause the impurities to segregate at the other end. The latter can be removed and the remainder of the ingot remelted and recast as before, and the process of removing the rela-

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tively impure end portions, remelting and recasting repeated as often as may be necessary to reach the desired value of P_0 .

In the modification illustrated in Fig. 2 means including an auxiliary emitter 25 are provided for adjustably controlling, in effect, the ratio P_0 of hole to electron concentration normally prevailing in filament 10, and increasing it above the value which is associated with thermal excitation alone and which is characteristic of the material at the operating temperature. This allows greater freedom in the choice of the semiconductive material, and it provides so sensitive a control of the hole-electron concentration ratio as to permit almost any desired approximation to effectively ideal intrinsic conductivity. Again, it makes possible, in effect, rapid variation or modulation of P_0 , as for the purposes hereinafter described.

The auxiliary emitter 25 in Fig. 2 makes contact with filament 10 just beyond the signal emitter. All of the emitters in Figs. 2 to 4 are shown as comprising rectifying point contacts but it is to be understood that any or all of them may take the alternative form shown in Fig. 1. The potential of the auxiliary emitter 25 relative to the contiguous portion of the filament is controlled by an adjustable voltage source connected between it and base 13, the source comprising a biasing battery 26 and associated adjustable potential divider 27. By-pass condenser 28 maintains emitter 25 at base potential for all signal frequencies. If filament 10 is of a material characterized by a preponderance of electrons over holes, such as n-type germanium, the emitter is so fabricated and biased in known manner as to inject holes into the filament to the substantial exclusion of electrons. The holes so injected continually drift toward the collector while additional electrons in equal concentrations maintain electrical neutrality throughout the filament, so that space charge does not occur. The concentration of holes and the concentration of electrons are thereby increased equally and substantially uniformly throughout all of filament 10 to the right of emitter 25. This tends to equalize the total hole and electron concentrations and makes possible a substantial effective increase in P_0 . In this manner substantially intrinsic conductivity can be achieved in the filament portion between auxiliary emitter and collector.

Under operating conditions the temperature of the filament will be maintained substantially above room temperature by virtue of the heating effect of the collector current derived from battery 17, but to minimize further heating of the filament, especially in the vicinity of the emitters, it is desirable to maintain the current attributable to the auxiliary emitter at the lowest possible value. With this objective in view it is advantageous to use semiconductive material for which the ratio P_0 at room temperature and thermal equilibrium is at least 0.2 and for which the absolute values of electron and hole concentrations are as low as possible. The selective injection of holes from the auxiliary emitter can then be relied upon to increase P_0 to at least 0.5 at the operating temperature, at which value the gain mechanism peculiar to the present invention appreciably manifests itself, or to a value above 0.8 where this mechanism is practically the exclusive gain-producing factor. To the extent that electron emission accompanies the desired hole emission from auxiliary emitter 25, the conductivity biasing current is unnecessarily increased and so also is the temperature of the filament. This factor can be minimized by designing auxiliary emitter 25 for maximum ratio f of hole emission to total carrier emission from that electrode. It is to be noted, nevertheless, that the carriers injected by emitter 25 will tend to reduce relative disparity in hole and electron concentrations in the filament as long as the proportion of the injected current carried by holes is greater than the proportion of total current normally carried by holes in the filament.

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The signal emitter 15 in Fig. 2 is longitudinally separated from the auxiliary emitter to protect the former against impairment of its function as an emitter of holes. Whereas low conductivity of the material underlying emitter 15 (whether it be a point contact or a stub of p-type material) is favorable for hole emission at that point, the profusion of holes injected by auxiliary emitter 25 tends to increase the conductivity. The latter holes flow toward the collector, however, and emitter 15 is not in their path. A separation of only a few mils will suffice to keep emitter 15 out of the influence of such holes as may diffuse against the field. A similar spacing is observed in Figs. 3, 4 and 5.

The Fig. 2 device operates as an amplifier of signals applied to its input circuit in substantially the same manner as the Fig. 1 device. It can be arranged to operate as a modulator, too, by applying one of the waves to be intermodulated to the signal input circuit and introducing the other wave into the circuit of auxiliary emitter 25 so that it varies the ratio P_0 in the filament. Thus, switch 29 in Fig. 2 can be operated to connect a source 30 of speech-bearing or other low-frequency modulating waves to emitter 25 for the purpose of modulating high-frequency carrier waves supplied through input transformer 18. The effect that varying P_0 has on the transconductance of the device will be treated further herein-after.

Fig. 3 illustrates a further modification in accordance with the invention which differs from the other substantially only in respect of the means provided for substantially equalizing electron and hole concentrations in the filament portion between signal emitter and collector. In this case the filament portion is exposed to sufficiently intense radiation of such character as to penetrate the semiconductive material and disrupt electron-pair bonds throughout the lattice structure, thus generating free electrons and holes in equal proportions.

For present purposes, the selected portion of a filament of germanium may be illuminated uniformly throughout its length with ordinary light, as suggested in Fig. 3, and the light intensity may be adjusted to secure the desired rate of electron and hole generation. Although the numerical difference between electron concentration and hole concentration is unaffected by the generation of holes and electrons in equal numbers, the ratio P_0 of hole to electron concentration tends toward unity, and the desired intrinsic condition, as the rate of generation is increased. The germanium selected for use in the Fig. 3 device should have a high initial value of P_0 at room temperature in order to minimize the reduction in filament resistance that accompanies illumination.

In lieu of the signal emitter 15 in Figs. 1 to 3 one may employ a signal-modulated light beam. Fig. 4 shows one embodiment, a modification of Fig. 2, in which light from a lamp 31 passes through a light valve 33 and is focused by a conventional optical system to a spot or line on the surface of filament 10 at the point occupied by signal emitter 15 in Figs. 1 to 3. The light valve 33, operated by a signal source not shown, varies the intensity of the spot of light in conformity with the variations in the instantaneous amplitude of the signal, thereby producing pairs of holes and free electrons that vary correspondingly in concentration. The electrons so produced pass through the filament to the base electrode, while the holes move in the opposite direction through the filament portion of intrinsic conductivity to the right of auxiliary emitter 25 and result in the conductivity modulation previously described. Although only half of the carriers generated by the optical signal are holes, the effect in the circuit shown is that of an emitter having an f of unity.

Further information regarding the construction and operation of the embodiments of the invention herein described is contained in the following mathematical analysis and explanation of the results achieved.

In the mathematical analysis for the filamentary tran-

sistor of the present invention, it will be supposed that a fraction f of the current from the signal emitter is carried by holes; the signal-modulated light beam emitter, for which there is no net emitter current, is equivalent to a current-carrying emitter which supplies holes at the same rate as the light beam and for which $f=1$. The condition $f=1$ holds approximately in general, as for example, through the use of an emitter stub of p-type semiconductor material of suitably high conductivity. Neglecting recombination of holes and electrons, which will not significantly affect the nature of the conclusions, and which is in general a good approximation, then for the steady biasing field sufficiently large that the hole flow is due primarily to drift under it rather than to diffusion, the internal current multiplication factor is

$$\alpha_e = \frac{b+P_0}{b(1-P_0)}(b+1) \left(f - \frac{P_0}{b+P_0} \right) \frac{1-e^{-i\omega t'}}{i\omega t'} \quad (1)$$

where, in the usual symbolic notation, i is the unit of imaginaries, b is the ratio of electron mobility to hole mobility, and ω is the angular frequency of the signal. The time t' is that required for the conductivity modulation to traverse the length of the filament, and it is given by

$$t' = \frac{b+P_0}{b(1-P_0)}t \quad (2)$$

where t is the time required for holes to drift the length of the filament under the applied biasing field. It will be understood further from these equations that large current multiplication factors may result from an increase in P_0 : as P_0 is increased from zero towards unity, the transit time t' for the conductivity modulation is increased over the drift time t in the ratio

$$(b+P_0)/b(1-P_0)$$

and that the current multiplication factor at zero frequency is increased approximately in the same ratio. Also, since the cut-off frequency, for which the square of the magnitude of α_e is one-half the zero-frequency value, is given by the condition that $\omega t'$ have some specific value (namely 2.79 radians, corresponding to a phase lag angle of 160 degrees), it follows that the product of the zero-frequency α_e and cut-off frequency is approximately constant with respect to changes in P_0 , and that cut-off frequency may be exchanged for gain by increasing P_0 .

A separate calculation of α_e for the ideally intrinsic case is desirable inasmuch as the foregoing equations assume a condition that it is impractical to maintain as P_0 is brought indefinitely closer to unity, viz., a biasing field E_a so high that the holes largely drift rather than diffuse:

$$E_a^2 \gg \frac{(1+P_0)(b+P_0)}{b(1-P_0)^2} \frac{kT\omega}{e\mu} \quad (3)$$

Here μ is the hole mobility, k is Boltzmann's constant, e is the electronic charge, and T is absolute temperature, so that kT/e is about $\frac{1}{40}$ volt at room temperature. The separate calculation of the internal current multiplication factor gives:

$$\alpha_e = (b+1) \left(f - \frac{1}{b+1} \right) \frac{1 - \operatorname{sech} \sqrt{i \frac{(b+1)\omega}{2bD}} x}{i\omega t} \quad (4)$$

where $D=kT\mu/e$ is the diffusion constant for holes and x is the length of the filament. It follows that the zero-frequency α_e is

$$\bar{\alpha}_e = \frac{(b+1)^2}{4b} \left(f - \frac{1}{b+1} \right) \frac{x^2}{Dt} = \frac{(b+1)^2}{4b} \left(f - \frac{1}{b+1} \right) \frac{eE_a x}{kT} \quad (5)$$

which increases in proportion to the filament length and to the biasing field. The latter does not affect the frequency behavior; the relative amplitude and phase of α_e

are readily computed, and are found to depend only on the variable

$$\theta = \frac{1}{2} \sqrt{\frac{b+1}{bD}} \omega x \quad (6)$$

which, in a given filament, depends only on frequency. Thus, for the filament from intrinsic material, increasing the biasing field increases the current multiplication but does not affect the cut-off frequency.

It might be noted that if there is some recombination present, the zero-frequency current multiplication factor α_e has a maximum with respect to changes in filament length x which occurs for this length equal to about $1.7L$, where the diffusion length $L=\sqrt{D\tau}$ is essentially the distance holes diffuse in their mean lifetime τ . For $1.1L < x < 2.74L$, $\bar{\alpha}_e$ is within 10 percent of its maximum, so that the choice of length is not extremely critical.

The intensity of illumination, or the conductivity biasing current, required to produce a prescribed value of P_0 can be estimated as follows:

If penetrating illumination is incident so that additional hole-electron pairs are generated essentially uniformly at the rate g per unit volume, then the quantity $P_0 \equiv p_0/n_0$ is increased to

$$\bar{P}_0 = \frac{(\bar{\tau}/\tau)(P_0+P_g)}{1+(\bar{\tau}/\tau)(P_0+P_g)-P_0} \quad (7)$$

where

$$P_g \equiv g\tau/n_0 = (g/g_0)P_0 \quad (8)$$

τ and $\bar{\tau}$ being respective mean lifetimes for holes before and after application of illumination, and g_0 the thermal rate of generation of holes. Now, $\bar{\tau}$ will in general not differ much from τ , so that, assuming $\bar{\tau}=\tau$,

$$\bar{P}_0 = (P_0+P_g)/(1+P_g) \quad (9)$$

If now the hole concentration is increased by injection, P_g may be redefined as $\Delta p/n_0$, where Δp is the added hole concentration, assuming negligible variation of Δp due to recombination. With this assumption, it is found that

$$P_g \equiv \Delta p/n_0 = \frac{(b+P_0)\bar{f}}{1-(b+1)\bar{f}}, \bar{f} \equiv fI_d/I_e \leq 1/(b+1) \quad (10)$$

where I_e is the total emitter current divided by the filament cross section, and I_d is the total current density.

The quantity $\bar{P}_0$ may now be found for the case of injected hole current by substituting for P_g .

Thus, for $\bar{\tau}=\tau$,

$$\bar{P}_0 = \frac{P_0 + b(1-P_0)\bar{f}}{1-(1-P_0)\bar{f}} \quad (11)$$

One of the salient features brought out in the foregoing analysis is the marked dependence of gain on P_0 for values of P_0 near unity, and it is this dependence that is responsible for intermodulation in Fig. 2. The same principle may be invoked in Figs. 3 and 4 by subjecting P_0 to control by one of the waves to be intermodulated.

Provision for adjustment of P_0 in amplifiers in accordance with the invention affords not only an effective gain control but also a band width control, for it has been demonstrated that band width, or cut-off frequency, is reciprocally related to gain. Fig. 5 shows qualitatively the gain-frequency characteristic of such an amplifier for two different adjustments of the conductivity bias. Below the lower of the two indicated cut-off frequencies f_c is a frequency band, appropriate for speech-signal or other intelligence transmission, over which the gain is fairly uniform at each setting of the gain adjuster. Between the two cut-off frequencies is another band in which by adjustment of P_0 , transmission can be enhanced or substantially suppressed at will.

The gain may be adjusted also by adjustment of the collector biasing voltage; increasing this voltage increases the gain-band width product, and in general augments the changes in gain and band width resulting from a given change in P_0 .

It has been pointed out that in the filamentary structures shown, the resistance in the collector circuit internally of the semi-conductor device is due predominantly, and almost exclusively, to the body resistance of the semiconductor material, and also that the attenuated cross section of the body accounts for the desirably high resistance of the collector current path. It should be understood, however, that these features can be realized also, in one degree or another, in structures that are not attenuated in cross section. For example, one can exploit the spreading resistance associated with a small-area electrode, as illustrated diagrammatically in Fig. 6. Here, the semiconductor body is in the form of a block 40 that is provided with a base electrode 43 in low-resistance ohmic (non-rectifying) contact with the lower surface of the block and a collector electrode 44 comprising a fine wire, the end of which makes low-resistance contact with the upper surface. The latter contact should be as nearly as possible an ohmic contact; and, in any event, it should be only so slightly asymmetrical that the body resistance between base and collector still largely accounts for the resistance between those electrodes. Also in contact with the upper surface of the block and closely adjacent the collector is the signal emitter 45, the latter comprising a rectifying point contact, for example, designed like emitter 15 of previous figures for carrier injection.

Since the collector current enters or leaves the body by way of the small-area collector contact, there is a crowding of base-collector current carriers in the vicinity of that contact and correspondingly high resistance in that portion of the current path. This "spreading resistance" is body resistance, and it is sharply distinguished from the current impeding effect associated with the barrier layer that can be formed under a point contact. Carriers injected by signal emitter 45 drift or diffuse into this spreading-resistance region and there produce conductivity modulation. For present purposes, this region should have substantially intrinsic conductivity, and the techniques described with reference to the filamentary structure can be invoked to achieve this condition. Thus, the entire block may be formed of germanium that has substantially intrinsic conductivity, or a conductivity biasing arrangement (including, for example, the auxiliary emitter 25) may be employed to make P_0 substantially unity in at least so much of the spreading-resistance region as accounts for the major part of the internal base-collector resistance. Alternatively, the body portion in the immediate vicinity of the collector contact can be subjected to heat, radiation, chemical, electroforming, or other treatment appropriate to convert extrinsic material into substantially intrinsic material.

Although the present invention has been described largely with reference to certain specific embodiments, various modifications within the spirit and scope of the invention will occur to those skilled in the art. It will be understood, for example, that p-type material may be substituted for n-type material if consistent changes are made elsewhere in the devices and that P_0 in such case will represent the ratio of negative carriers to total carriers. It will be understood, too, that the several devices disclosed for control of P_0 can be interchanged or combined, as desired.

What is claimed is:

1. An electric signal amplifier comprising a filament of semiconductive material, a pair of electrodes making low resistance contact with said filament at opposite ends thereof, an emitter in contact with said filament adjacent one of said electrodes for injecting charge carriers into the filament, at least the major portion of said filament adjacent said emitter and extending toward said other electrode being of substantially intrinsic material in which the difference between the number of free holes and the number of free electrons present is less than the number of free hole-electron pairs, a signal input circuit connected between said emitter and the adjacent electrode, and a signal output circuit connecting said pair of electrodes including a unidirectional voltage source for sweeping the charge carriers injected by said emitter towards said other electrode.
2. A signal amplifier in accordance with claim 1 further characterized by means including a light source for irradiating said portion for making the material of said portion exhibit substantially intrinsic conductivity.
3. A signal amplifier in accordance with claim 2 further characterized by an auxiliary emitter in contact with said filament at a region intermediate between the first-mentioned emitter and said other electrode.
4. An electrical translating device comprising a filament of semiconductive material, a pair of electrodes making low resistance contact with said filament at opposite ends thereof, and an emitter in contact with said filament adjacent one of said electrodes, at least the major portion of said filament adjacent said emitter and extending toward said other electrode comprising substantially intrinsic material in which the difference between the number of free holes and the number of free electrons present is less than the number of free hole-electron pairs.
5. An electrical signal device in accordance with claim 4 in combination with means for substantially equalizing the numbers of holes and electrons in said major portion of said filament between said emitter and said other electrode whereby said portion exhibits substantially intrinsic conductivity.
6. An electrical signal device according to claim 5 in which said equalizing means comprises a light source for irradiating said portion of said filament to exhibit substantially intrinsic conductivity.

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