LB-953

THE EFFECTIVE SURFACE RECOMBINATION OF A GERMANIUM SURFACE WITH A FLOATING BARRIER

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Approved

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Introduction

It is now recognized that the physical and chemical condition of the free surface is of great importance in the operation of germanium devices. The recombination of carriers, the reverse saturation current, the reverse breakdown, stability and noise are all influenced by the presence or absence of surface layers. It is difficult to discuss the properties of these layers theoretically because of their elusive chemical nature. The usual procedure is to treat the surface with various etches or ambients, measure the changes in electrical properties due to the treatments and then postulate the shape of the energy band structure at the surface. In this bulletin this procedure is reversed. Starting with surfaces which have well-known energy band structures, the behavior of the surface recombination velocity is predicted on the basis of one-dimensional junction theory, and then measurements are made in practical cases to determine the validity.

The surface layers chosen for the analyses were heavily doped p and n-type regions on n-type base as obtained by alloying, and metallic plating on n-type base as obtained by electroplating. The computation in this bulletin shows that the surface recombination velocity should be as low as 1 cm/sec for the alloy surfaces, while for the plated surface it should be several thousand. The low predicted surface recombination for the alloy surfaces comes about for the same reason that the injection efficiency of alloy junctions is high; the alloy junction is a very efficient emitter of minority carriers into the base and a poor acceptor of majority carriers from the base because of the high doping level in the alloyed region. Since recombination in the surface layer of minority carriers from the base requires both majority and minority carriers, the restriction of the flow of either reduces the surface recombination.

However, measurements of surface recombination by diffusion and pulse drift methods on alloy junction surfaces indicate that their apparent recombination is considerably higher than predicted and, in fact, is about the same as that of adjacent untreated surface, e.g., 300-500 cm/sec. It is shown that lateral current flow, due to minority carrier gradients parallel to the junction interface, and neglected in one-dimensional theory, gives rise to circulating currents which translate the minority carriers to the nearest high recombination surface. Thus the theoretical reduction in surface recombination is not obtained with alloy surface junctions. The high surface recombination predicted for plated layers is obtained in practice.

The hole translation property of the floating p-layer is used herein to explain the erroneously high lifetimes often observed by diffusion measurements on silicon and p-type germanium. In these materials a layer of opposite conductivity type is formed by etching processes which acts like the floating alloy layer described above. Because the p-n junction so formed is parallel to the surface, the measurement of minority carrier concentration vs distance gives a result which is not characteristic of the base material. The pulse drift method of lifetime measurement is free of this difficulty.

Interpretation of the effective lifetime measurement on completed transistors, when made by pulsing the emitter with the collector floating (*LB-934*)[8], can also be affected by hole translation (p-n-p transistor). If the collector physically penetrates far into the base wafer, the feed-out of holes from the edges of the collector during the decay time translates the recombining surfaces of the wafer closer together, reducing the measured lifetime. Under such conditions, the actual lifetime in an operating transistor is greater, since this hole translation does not take place when the collector is biased in the normal way.

It is hoped that this study of the relatively simple alloy surface layer will aid in the understanding of the more complex chemical surface layers often found on etched germanium surfaces and which are apparently responsible for much of the difference between actual and theoretical performance of semiconductor devices.

I. General Discussion

The rate of recombination of minority carriers at free surfaces often plays a dominant role in determining the characteristics of semiconductor devices. For example, the current amplification-factor of a transistor is usually determined by surface recombination more than by any other quantity.[1,2] Thermal generation of minority carriers, which is related to both surface and volume recombination, results in saturation current in rectifiers and transistors. In many devices, the free surfaces contribute most of this generally undesirable saturation current. In some photoconductor devices, surface recombination limits sensitivity.

Surface recombination can be expressed quantitatively through the surface recombination velocity, "s".[3] The rate at which minority carriers recombine is proportional to the product of their concentration and s. In theory s is a characteristic of the surface and may have any value between zero and thermal velocity (about 10^7 cm/sec). Experiments on germanium surfaces show that s depends on the surface treatment and that values ranging from about 50 cm/sec to several thousand cm/sec may be obtained by different chemical treatments.[1,4] To reduce surface recombination, we are interested in treatments which result in very low values of s.

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[1] *LB-916, The Variation of Current Gain with Junction Shape and Surface Recombination in Alloy Transistors.*

[2] *LB-917, On the Variation of Junction Transistor Current-Amplification Factor with Emitter Current.*

[3] Shockley, W., HOLES AND ELECTRONS IN SEMICONDUCTORS, p. 321, D. Van Nostrand Co., New York; (1950).

[4] Conwell, E. M., "Properties of Silicon and Germanium", *Proc. I.R.E.*, Vol. 40, No. 11, p. 1352; 1952.

A variety of models of the surface which might give low surface recombination velocity can be imagined. Three which are experimentally attainable with reasonable certainty are illustrated in Fig. 1. They all imply the addition or production of a film on the surface which has different electrical characteristics than the bulk. These three possibilities are: (1) a metallic film, (2) a layer of opposite conductivity type, and (3) a layer of the same conductivity type but of higher conductivity. Plating techniques permit a metallic layer to be formed and the change of conductivity may be accomplished by alloying[5] or diffusing impurities into the surface.[6] While many other surface models are possible, these three are easily analyzed and should permit comparison of theory with experiment. The present work evaluates the possibilities for reducing s by these means in terms of a simple one-dimensional analysis and discusses some preliminary experimental results.

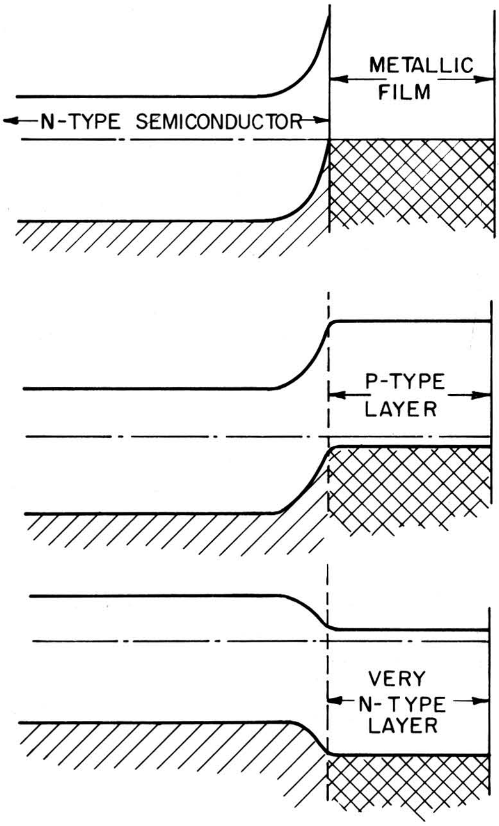

Fig. 1 - Energy level diagrams for three possible types of surface barrier.

2. Theory

In this section, equations are given which may be used to predict the rate of surface recombination for metallic and n and p-type films on n-type material. The same reasoning can of course be applied to films on p-type material. The treatment is one-dimensional for simplicity and is therefore subject to the assumption that no parameters vary appreciably along the surface. The discussion of experimental results which follows shows that this condition can be troublesome in practice.

One can see intuitively why surface layers such as these are hopeful. In all cases, a barrier exists near the surface to one type of carrier or the other. Since both holes and electrons must be present for recombination, restraining the flow of either should reduce surface recombination.

The approach of this section is as follows: First, an equivalent surface recombination velocity (s) is defined for p and n-type surface layers and evaluated in terms of recombination in the film. Following this an equation for s for a metallic surface is given and an approximate value computed. Finally, a relation between s and γ ("emitter efficiency" of the layer if it were used as the emitter of a transistor) is demonstrated.

2.1 n and p Type Layers

2.10 Definition of Equivalent s

The equivalent surface recombination velocity for a surface with a semiconducting layer on it will be called s and will be defined as follows:

Consider the situation of an n-type semiconductor with a surface layer d cm thick and composed of the same material but of different conductivity. The energy band configuration for both cases of interest and the pertinent parameters are labeled in Fig. 2. Holes and electrons recombine in the surface layer by both surface and volume recombination. To maintain non-equilibrium steady state densities of minority and majority carriers in the surface layer, holes and electrons must flow in equal numbers from the bulk into the surface layer. Further, this flow must equal the net recombination rate in the surface layer. This results in two equal current densities (J_e and J_p). The effective surface recombination velocity will be defined as:

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[5] Law, R. R., Mueller, C. W., Pankove, J. I., and Armstrong, L. D., "A Developmental Germanium p-n-p Junction Transistor", *Proc. I.R.E.*, Vol. 40, No. 11, p. 1352, 1952.

[6] R. N. Hall and W. C. Dunlap, "P-N Junctions Prepared by Impurity Diffusion", *Phys. Rev.*, Vol. 80, p. 467; 1950.

$$s = \frac{J}{q(p_n - p_o)} \qquad (1)$$

where $J = J_e = J_p$, p_o is the equilibrium value of p_n, and q is the electronic charge. ($p_n - p_o$ is the excess hole density in the bulk.) This is the value of surface recombination velocity which one would measure by any of our present techniques.[7, 8, 9]

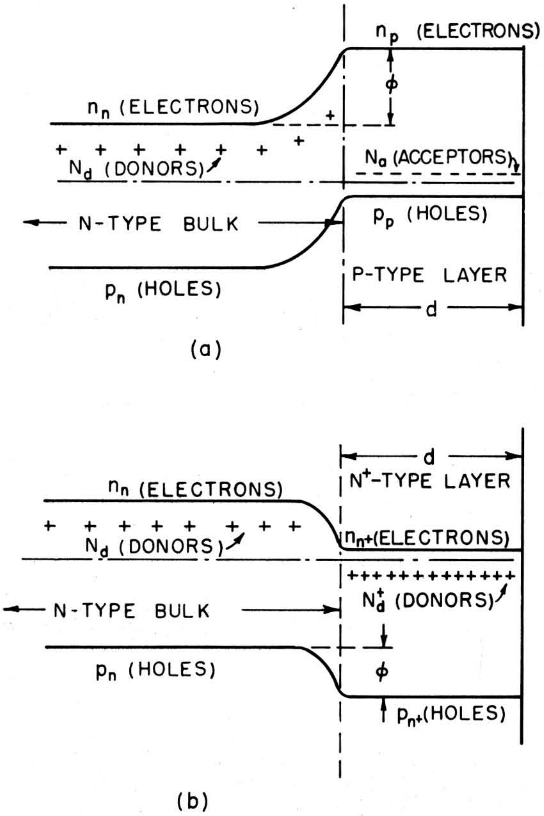

Fig. 2 – Detailed energy level diagram for (a) p-type layer on n-type base and (b) strongly n-type layer on an n-type base.

So that the general considerations may apply to either p or n-type layers we will identify the minority carrier density in the surface layer with the letter m, and its equilibrium value with m_o. J is determined by the minority carrier lifetime in the surface layer (τ), the surface recombination velocity for minority carriers (s_m) at the actual surface; the thickness of the surface layer (d), and the excess minority carrier density ($m-m_o$) in the surface layer. The minority carrier determine the recombination rate in the surface layer regardless of whether they are electrons or holes.

Two approximate expressions for J are:

$$J \approx q(m-m_o)\left(\frac{d}{\tau}+s_m\right), \text{ when } d<L_m \text{ (i.e., for thin layers)} \qquad (2a)$$

$$J \approx q(m-m_o)\,\frac{L_m}{\tau} = q(m-m_o)\,\frac{D_m}{L_m}, \text{ when } d>L_m. \qquad (2b)$$

D_m and L_m are the minority carrier diffusion coefficient and diffusion length, respectively, in the surface layer.

Combining Eqs. (2a) and (2b) with Eq. (1):

$$s = \left(\frac{d}{\tau}+s_m\right)\frac{(m-m_o)}{(p_n-p_o)}, \text{ when } d<L_m \qquad (3a)$$

and

$$s = \frac{D_m}{L_m}\,\frac{(m-m_o)}{(p_n-p_o)}, \text{ when } d>L_m. \qquad (3b)$$

The ratio of the steady-state excess minority carrier densities, $(m-m_o)/(p_n-p_o)$, are now calculated for n and p-type layers.

2.11 p-type Surface Layer

The ratio $(m-m_o)/(p_n-p_o)$ depends on the conductivities of the bulk and surface layer. Consider first a p-type surface layer with acceptor density N_a as shown in Fig. 2a. The electron density in the p-type material, n_p, is the minority carrier density, m, in Eqs. (3a) and (3b). Thus, what is desired is (n_p-n_o) to replace $(m-m_o)$ in the general expressions for s.

Four basic equations link the densities of holes, electrons, donors, and acceptors with the barrier height, φ:

$$n_n = N_d + p_n, \qquad (4a)$$

$$n_p + N_a = p_p, \qquad (4b)$$

$$n\, e^{\frac{-q\varphi}{kT}} = n_p, \qquad (4c)$$

and

$$p_n = p_p\, e^{\frac{-q\varphi}{kT}} \qquad (4d)$$

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[7] Valdes, L. B., "Measurement of Minority Carrier Lifetime in Germanium", *Proc. I.R.E.*, Vol. 40, No. 11, p. 1420, 1952.

[8] *LB-934, Measurement of Minority Carrier Lifetime and Surface Effects in Junction Devices.*

[9] Stevenson, D. T. and Keyes, R. J., *Bull. Am. Phys. Soc.*, Vol. 29, No. 3, p. 18.

The first two equations indicate charge neutrality in the surface layer and bulk and the the second pair relate the hole and electron concentrations on either side of the boundary. The only assumptions involved in applying these equations are (1) net electrical neutrality except in the depletion layer at the boundary and (2) s is reasonably small (compared to thermal velocity). Both are sufficiently satisfied. These equations (4) may be combined to yield an expression linking n_p and p_n:

$$p_n^2 + p_n N_d = n_p^2 + n_p N_a \qquad (5a)$$

and the same form applies to the equilibrium densities:

$$p_o^2 + p_o N_d = n_o^2 + n_o N_a. \qquad (5b)$$

Combining these to yield the form needed to calculate s is difficult. However, we may make some simplifying assumptions. In the event that N_a is very large (a very p-type surface), n_p^2 is negligible compared to $n_p N_a$. If, in addition, $N_d >> p_n$, we can write very simply

$$\frac{n_p - n_o}{p_n - p_o} \approx \frac{N_d}{N_a} \qquad (6a)$$

N_d/N_a may now be substituted into Eqs. (3a) and (3b) in place of $(m-m_o)/(p_n-p_o)$ to calculate s. Under conditions of high injected hole density in the bulk, p_n may not be negligible compared to N_d. However, it will then be great compared to p_o and we may write

$$\frac{m-m_o}{p_n-p_o} \approx \frac{n_p-n_o}{p_n} \approx \frac{p_n+N_d}{N_a} \qquad (6b)$$

Thus, at high levels of p_n, s will increase linearly with hole density in the n-type material.

Substitution of Eq. (6a) into (3a) and (3b) yields:

$$s = \left(\frac{d}{\tau}+s_m\right)\frac{N_d}{N_a} \text{ for thin layers,} \qquad (7a)$$

and

$$s = \frac{D_m}{L_m}\frac{N_d}{N_a}, \text{ for thick layers (compared to } L_m). \qquad (7b)$$

L_m and D_m apply to electrons in the surface layer. These equations apply for low injection levels $(p_n << N_d)$.

2.12 n^+ Surface Layer

The form of the equivalent expressions for s for the case of a very n-type layer is similar and may be derived in much the same way. Here, holes are the minority carriers in both the surface layer and the bulk. The symbol "+" refers to characteristics in the surface layer as indicated in Fig. 2b.

We can write four equations similar to those used for the case of the p-type surface:

$$n_n = p_n + N_d \qquad (8a)$$

$$n_{n+} = p_{n+} + N_d^+ \qquad (8b)$$

$$n_n = n_{n+}\, e^{\frac{-q\varphi}{kT}} \qquad (8c)$$

$$p_{n+} = p_n\, e^{\frac{-q\varphi}{kT}} \qquad (8d)$$

These equations are of the same form as Eq. (4). The difference is that n_p, n_o, and N_a of Eqs. (5a) and (5b) are replaced by p_{n+}, p_{o+}, and N_d^+, respectively. Subject to similar assumptions, the solutions will be of the same form as Eqs. (7). Thus we have:

$$s = \left(\frac{d}{\tau}+s_m\right)\frac{N_d}{N_d^+}, \text{ when } d<L_m, \text{ and} \qquad (9a)$$

$$s = \frac{D_m}{L_m}\cdot\frac{N_d}{N_d^+}, \text{ when } d>L_m, \qquad (9b)$$

where D_m and L_m apply to holes in the surface layer.

2.13 General Expressions for s

In the case of a surface layer which is thick compared to a minority carrier diffusion length within it we have Eqs. (7b) and (9b). We may now use the Einstein relationships $\left(D_p = \frac{kT}{q}\mu_p \text{ and } D_n = \frac{kT}{q}\mu_n\right)$ and introduce $\sigma_b \approx q\mu_n N_d$ (the conductivity of the bulk material) and σ_s (the conductivity of the surface layer).

For the n^+ type layer, $\sigma_s = q\mu_n N_d^+$, while for the p-type layer, $\sigma_s = q\mu_p N_a$. By manipulation, both Eqs. (7b) and (9b) become:

$$s = \frac{D_p}{L_m}\frac{\sigma_b}{\sigma_s};\ (d>L_m). \tag{10}$$

It should be emphasized that D_p is the hole diffusion coefficient in the surface layer. Because of impurity scattering this may be lower than D_p in the bulk.

Similarly, a generalized expression for Eqs. (7a) and (9a) may be written which apply to thin layers:

$$s = \left(\frac{d}{\tau}+s_m\right)\frac{\sigma_b}{\sigma_s}\cdot\frac{\mu_s}{\mu_b}\ \text{when } d<L_s. \tag{11}$$

Here, τ is the minority lifetime in the surface layer, s_m is the true surface recombination velocity of the layer, μ_s and μ_b are majority carrier mobilities in the surface layer and bulk, respectively. μ_s will be less than the value measured in relatively pure material because of impurity scattering, and possibly scattering at the surface.

2.14 Evaluation of p and n Layers

It is difficult to evaluate Eq. (11) in that τ and s_m for highly doped semiconductors have not been measured. If we assume, however, that d is sufficiently small that d/τ is dominated by s_m, and assume further that s_m is of the same order of magnitude as surface recombination values already obtained (say 1,000 cm/sec to be conservative), then s may be of the order of a one cm/sec when $\sigma_b/\sigma_s = 10^{-3}$. Eq. 10 is easier to consider because the term $\sigma_s L_m$ is the familiar one which enters into the expression for the efficiency of an emitter. Previous work suggests that $\sigma_s L_m$ has the value of about 1.6 mhos in alloy junctions in germanium.[2] Now, if σ_b is assumed to be 0.2 mhos/cm and $D_p \approx 6$ cm²/sec (consistent with heavily doped germanium), then s = 0.75 cm/sec. This is a very hopeful result. There is no reason to prefer a p-type layer to an n-type layer of equal conductivity as far as values of s are concerned. However, the latter would be preferable in many cases for other reasons (e.g., there would be no tendency to produce surface short-circuit paths from emitter to collector of a transistor).

2.2 *Metal Films*

The above analysis only applies when the surface layer is also a semiconductor and has the same energy gap as the bulk. To add to the picture, surface layers with different energy gaps should be discussed. In particular, the case of a metal film deserves attention.

An expression for s can be computed for the case of a metal-semiconductor contact such as illustrated in Fig. 3. The derivation is straightforward and so will not be given; the result is:

$$s \approx \frac{\sigma_b^2}{\sigma_i^2}\,\frac{(1+b)^2}{B^2}\,\frac{\bar{c}}{4}\,e^{\frac{-q}{kT}(\varphi_o-\varphi_e)} \tag{12}$$

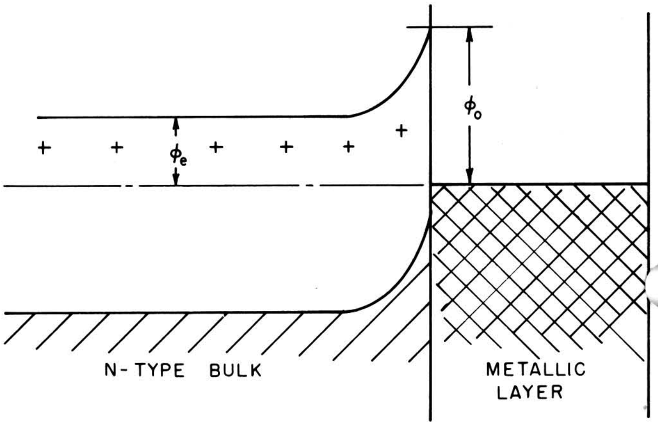

Fig. 3 - Detailed energy level diagram for a metallic layer on an n-type base.

Here, σ_i is the conductivity of the intrinsic semiconductor, $\bar{c}$ is mean thermal velocity ($\sim 10^7$ cm/sec at 300 degrees K). φ_o and φ_e are labeled in the figure, and $b = \mu_n/\mu_p$. This equation is derived assuming diffusion flow for holes and "diode" flow for electrons crossing the barrier.[10]

Evaluation of Eq. (12) requires a knowledge of $\varphi_o - \varphi_e$. 0.3 electron volt has been estimated for this quantity by Schwartz and Walsh for 5 ohm-cm germanium in connection with the surface-barrier transistor[11]. If N_d for ohm-cm n-type germanium and 0.3 electron volt for $\varphi_o - \varphi_e$ are substituted into Eq. 12, a

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[10] Bradley, W. E., "Principles of the Surface-Barrier Transistor", *Proc. I.R.E.*, Vol. 41, No. 12, p. 1702, (1953).

[11] Schwarz, R. F. and Walsh, J. F., "Properties of Metal Semiconductor Contacts", *Proc. I.R.E.*, Vol. 41, No. 12, p. 1715, (1953).

value for s of 3,500 may be computed. This calculated value is of the same order as the surface recombination velocity measured for a copper plated surface 7,400 cm/sec.[1] Thus, at present, the evidence suggests that metal films will give values of surface recombination velocity which are much larger than those easily attained with chemical treatments.

2.3 Relation to Emitter Efficiency

Consider Fig. 4 which shows a diode made by connection to the semiconductor bulk and to the surface layer. The currents J_b and J_s labeled according to the direction of carrier flow when the diode is biased in the forward direction. Their ratio defines the emitter efficiency γ of a transistor which might be made using the surface layer as an emitter and the bulk material as the base region. The approximate relation is:

$$\frac{1-\gamma}{\gamma} = \frac{J_b}{J_s} \cdot \frac{W_b}{L_p}, \qquad (13)$$

where W_b is the emitter-collector spacing of the transistor.[12] For a p-n-p transistor,

$$\frac{1-\gamma}{\gamma} = \frac{\sigma_b W_b}{\sigma_s L_p}$$

where L_p is the hole diffusion length in the emitter. This is also the result of multiplying Eq. 10 by W_b/D_p, since L_p and L_m are identical.

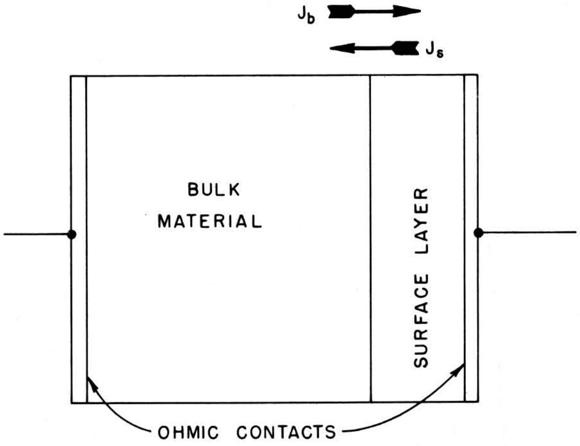

Fig. 4 – Hypothetical diode formed by connection to the bulk material and to the surface layer. The arrows show the direction of carrier flow when the diode is biased in the forward direction.

$$\frac{1-\gamma}{\gamma} = s\frac{W_b}{D_p}. \qquad (14)$$

This relation is actually quite general. It applies to the metallic film of the surface-barrier transistor and even for an n^+ surface layer and what might be called $n^+ - n - n^+$ transistor. In fact, Eq. 14 may be derived directly from the diode equations in such a way that the relation between s and γ emerges as fundamental. While such a procedure suggests a more direct way of deriving s for different surface layers, it is less easy to consider in physical terms than the preceding development. The connection between s and γ suggests that one may be evaluated from a measurement of the other.

It is worth pointing out that s is dependent on injection level in the same way as γ. Thus, the rate of surface recombination would be expected to go as the square of p_n when p_n becomes large compared to N_d. This is not usually observed in chemically treated samples which probably indicates that none of the simple models considered here may be applied to such surfaces.

3. Experimental Observations

The rather small values of s predicted by theory for a floating surface layer of opposite conductivity type should be directly measurable. A series of experiments which will be described in detail have been made to test this theory for the case of a very p-type layer on an n-type sample. The expected reduction in s is not obtained. It is by examination of these negative results that an opposing mechanism is revealed which contributes to our understanding of the floating barrier.

3.1 Lifetime Measurements

3.10 Diffusion Method

Surface recombination velocity is usually obtained by measuring the actual (often called "effective") lifetime of minority carriers in a sample of known volume lifetime and dimensions. Then s is obtained by computation for the specific geometry. For the case of a rectangular

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[12] Shockley, W., Sparks, M., and Teal, G. K., "P-N Junction Transistors", *Phys. Rev.*, Vol. 83, pp. 151, 162; 1951.

bar of cross sectional dimensions B and C, Shockley gives the first order formula:[8]

$$1/\tau_m = 1/\tau_v + \nu_s \qquad (15)$$

where $\nu_s = 2s\left[\frac{1}{B} + \frac{1}{C}\right]$ holds for small s.

Lifetime can be measured by the diffusion method in which the minority carrier density is measured as a function of distance from a line of light. If a thin bar is used, the measured lifetime will be largely surface controlled, thus providing a simple measure of s on the large surfaces. If the thickness of the bar is W, then $s = W/2\tau_m$ when s is the same on both surfaces.

A sample in the form of Fig. 5 was used. One side of the bar carried a large indium alloy junction. This was the surface whose effective s was to be determined. The point contact and line of light were on the opposite side of the bar. Measurements could also be made on a region of the bar which did not have the floating junction layer. One might expect that the region including the junction, which theory predicts will have one side where $s \approx 0$, would show a longer lifetime by about a factor 2, compared to the rest of the sample. This is because one half of the surface sink is effectively removed. The situation is the same as if the bar had been increased to twice its thickness, thereby decreasing ν_s by a factor two. Since the bar was known to have a volume lifetime in excess of several hundred microseconds, this would result in a doubled τ_m

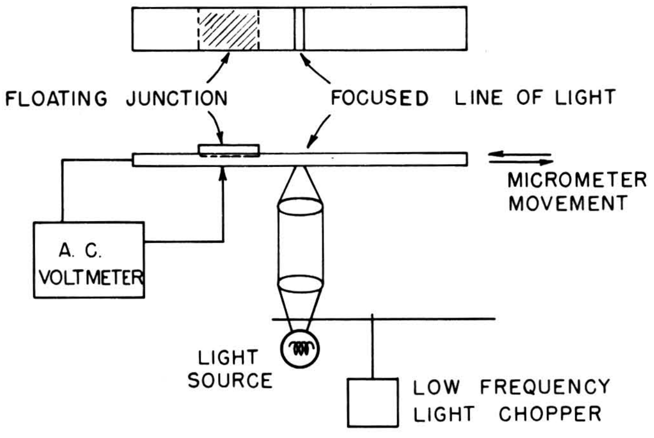


Fig. 5 - Apparatus for measurement of lifetime by the diffusion method on a germanium bar carrying a floating alloy junction.

The results of such a measurement are shown in Fig. 6. The log of the open circuit probe voltage in arbitrary units is plotted against the distance between the probe and the light line. When this spacing is less than the thickness of the bar, the slope of the curve yields a lifetime of 90 μsec. This is about the same as the value measured at positions far removed from the floating alloy junction. As the light line is moved further than the bar thickness from the probe, the slope of the curve becomes practically zero, indicating an apparent lifetime of many thousands of microseconds. This is far in excess of the expected factor of two. When the light line passes the edge of the floating p-layer, the curve resumes its original slope, characteristic, as before, of the lifetime far removed from the junction.

The apparent increase in lifetime cannot be explained on the basis of a reduced s on one surface. Additional experiments to be described were performed on the same bar in an effort to find the reason for the discrepancy.

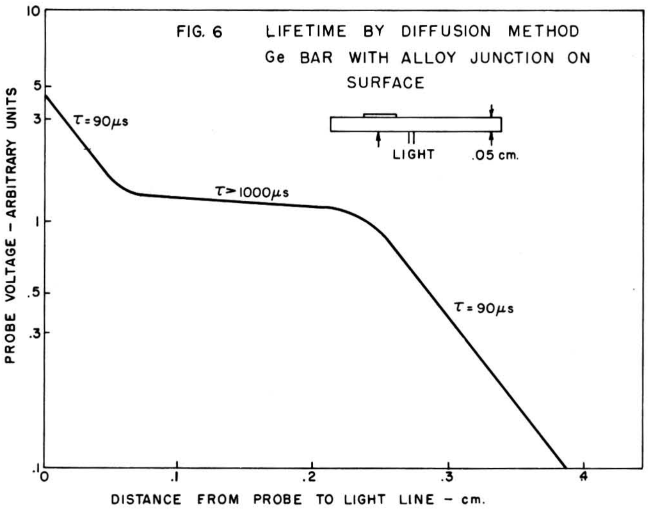


Fig. 6 - Curve obtained by plotting probe voltage vs. distance from probe to light line, using apparatus of Fig. 5.

3.11 Drift Method

Another way to determine lifetime in the bar is to measure the time decay of excess conductivity after a pulse excitation of hole-electron pairs by a short flash of light.[9] In this measurement the conductivity variation is obtained from the voltage across a resistor in series with the sample and a bias battery. If the resistor is matched to the dark resistance of the sample, the light pulse is of low intensity so that $\Delta\sigma << \sigma$, and the field across the sample is sufficiently small such that the transit time of carriers due to the electric field is long compared to the decay by recombination, then

$$\frac{\Delta\sigma}{\sigma} = \text{const } e^{-t/\tau} \qquad (16)$$

This method measures lifetime directly, instead of obtaining it through the diffusion relation $L = \sqrt{D\tau}$, as in the previous experiment.

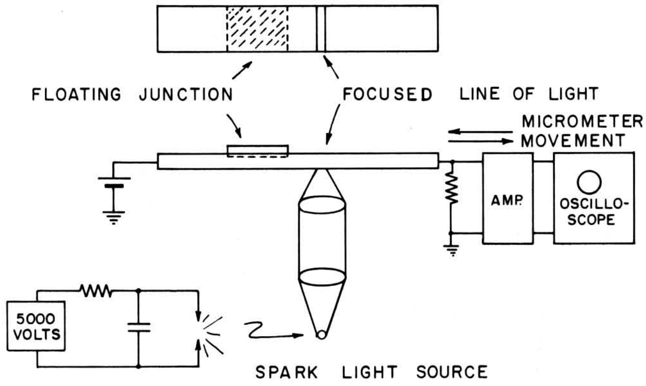


Fig. 7 - Apparatus for measurement of lifetime and drift mobility by the drift method on a germanium bar carrying a floating junction.

The experimental arrangement is shown in Fig. 7. The light source is a spark discharge in air operated as a relaxation oscillator from a 5000-volt power supply. When focused on the sample, the spark produces a line of light which was arranged perpendicular to the long axis of the sample. A micrometer screw enables the sample to be moved parallel to this axis so that the lifetime could be measured by the change in the voltage drop across a resistor connected in series with the sample and a bias battery. The measurement is made with an oscilloscope with a built-in delay line so that the entire trace can be studied. If the photoconductivity decays exponentially (as it should from Eq. 16) the lifetime can be read directly on the oscilloscope face as the 1/e point.

At positions far removed from the floating junction, the decay time corresponded to 90 μsec, in agreement with the diffusion length measurement. In the floating junction region the decay departed from an exponential and could not possibly be construed as a doubling of the lifetime. The detailed nature of this curve will be discussed later in connection with the drift time measurement. For the present the conclusion is that the expected doubling of the decay time was not observed.

3.12 Diode Measurements

A measurement of the effective minority carrier lifetime in the base region of an alloy junction diode can be obtained by injecting minority carriers into the region with a pulse of forward current. The decay is then followed by observing the open circuit emitter voltage as a function of time.[8] The same measurement can be made in a transistor in which the collector is allowed to float electrically. If the base wafer is thin, the effective lifetime is a measure of s. Furthermore, most of the surface recombination will take place on the surface opposite the alloy junction provided s is the same value there as at other surfaces. Now if we substitute a large floating collector for the surface opposite the emitter, as in an alloy transistor, and if this surface actually has a very low value of s as predicted by the junction theory already given, one would expect a marked increase in the effective lifetime. Such measurements were made on a series of transistors and diodes of essentially identical emitter-base region geometry. Both diodes and transistors gave the same value of effective lifetime within experimental error. Thus again, the expected reduction in s was not observed.

3.2 The Feed-in Feed-out Effect

The negative results in the above experiments require examination and modification of the theory of surface recombination velocity at a floating junction. The most logical explanation appears to be connected with the fact that the p-type germanium on the surface is a good conductor (relatively) and hence, is equipotential. Under conditions of an applied field within the n-type bar, or when a gradient of minority carrier density exists along the interface, the floating junction assumes the dual role of emitter and collector. While the net current across the junction is zero, this need not be true at every point. In fact, the effective s may be the same as for adjacent germanium surfaces. The p-region then acts as a translator of holes rather than as a low s interface. Some additional experiments which support this view will now be described.

3.20 Floating Potential Measurements

Indirect measurements indicate that the p-layer in an alloy junction has a resistivity of the order 0.001 ohm-cm. If an electric field is maintained in a bar which carries a floating junction, and if the bar has a resistivity of the order 1 ohm-cm, the p-layer can be considered as an equipotential surface. The situation is illustrated in Fig. 8. The layer will float at some potential intermediate between the potential V_b and V_a. Part of the junction is biased in the reverse direction, collecting thermally generated holes from the n-type bar, while the rest is biased in the forward direction, injecting holes back into the bar closer to the negative electrode. The net current across the junction is zero, since the p-layer is floating. No holes are lost in the process. Because the hole concentration in the p-type layer is much higher than the electron concentration in the n-type bar, most of the current crossing the junction in either direction will consist of holes. The hole currents will furthermore be small compared to the main electron current in the n-type bar. Hence it can be assumed that the electric field in the bar is not seriously disturbed by the presence of the junction.

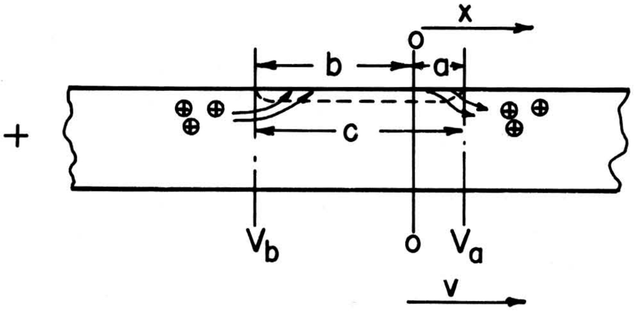


Fig. 8 - Diagram for the calculation of the floating potential of the alloy junction.

The floating potential of the junction may be calculated by equating the integrated current for the forward biased region to that for the reverse biased region. One may take the position at which the potential in the germanium is equal to the p-layer potential as the zero of x and v. If the total potential drop $V_a - V_b$ is called V and the total length of the p region a - b is called c, then v = x/c V. Then

$$\int_{-b}^{o} \left(e^{\frac{qVx}{kTc}} - 1\right) dx = \int_{o}^{a} \left(e^{\frac{qVx}{kTc}} - 1\right) dx$$

One can then solve for the floating potential V_f with respect to V_a ($V_f = \frac{a}{c} V$):

$$V_f = \frac{kT}{q} \ln \left[\frac{qV/kT}{1-e^{-qV/kT}}\right] \qquad (17)$$

Fig. 9 shows the result of a test of this equation. Both the floating potential and the total potential drop were measured by means of probes and a high-impedance millivoltmeter. Inasmuch as there are no adjustable constants in this equation, the agreement is considered as satisfactory evidence of the feed-in feed-out phenomenon.

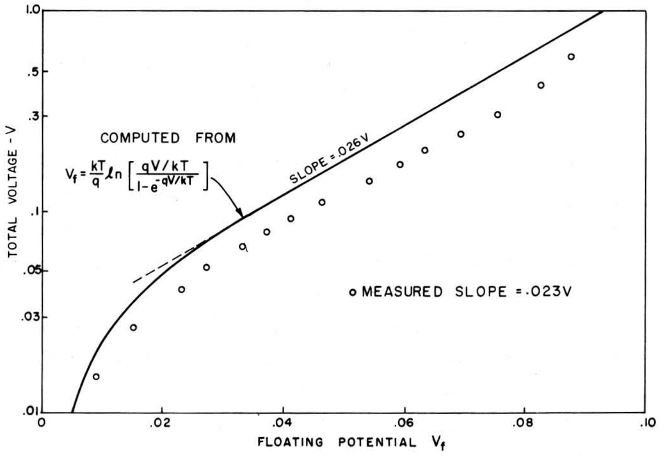
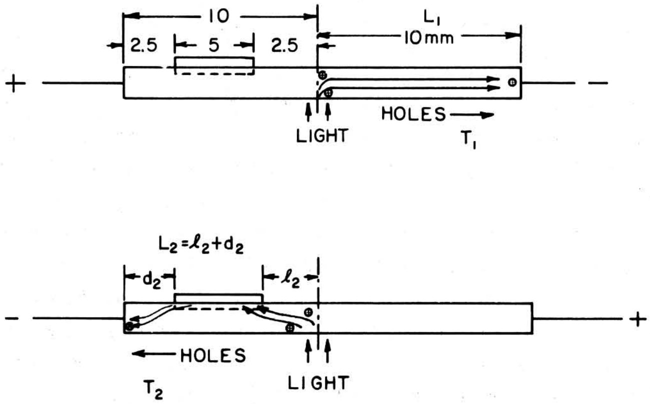


Fig. 9 - Results of measurement of the floating potential and comparison with Eq. 17.

3.21 Mobility or Drift Time Measurements

The previous experiment suggests that holes can be translated towards a negative electrode through a p-type surface layer. It is presumed that this process occurs almost instantaneously, i.e., if a hole is fed into the reverse biased junction region another hole is immediately emitted at the forward biased region. Thus, if the hole drift time in an electric field is measured on a bar carrying a floating junction, an artificially short drift time should be observed due to the bypassing action of the floating junction. The same pulse lifetime equipment described in connection with lifetime measurements was used to test this conjecture except that the field in the bar was increased to the point at which the drift time was shorter than the lifetime.



$$T_2/T_1 = .47$$

$$L_2/L_1 = .50$$

Fig. 10 - Measurement of drift time in the germanium bar when (a) holes are confined to the bar volume and (b) when holes bypass the bar through the floating junction region.

The light pulse which acts as the hole source was focused at the center of the bar and the drift time measured for holes drifting first toward the end without the floating junction, and then, by reversal of the polarity of the electric field, for holes drifting through the part of the bar carrying the junction. Fig. 10 shows the two cases. From the dimensions of the bar and the length of the junction region, the drift time should have been halved for the second case. The measured ratio was 0.47.

Additional drift experiments using a light line movable along the bar have all confirmed the picture of instantaneous hole translation through the p-region. One point which was of special interest was the explanation of an unusual spike on the decay curve during pulse lifetime measurements in the vicinity of the floating junction. This is illustrated in Fig. 11. Initially (region I) a sharp spike occurs, beginning immediately after the light injection pulse. Then the carriers decay exponentially and simultaneously drift in the electric field, as in region II. Finally, carriers reach the end of the sample and the conductivity falls, as in region III.

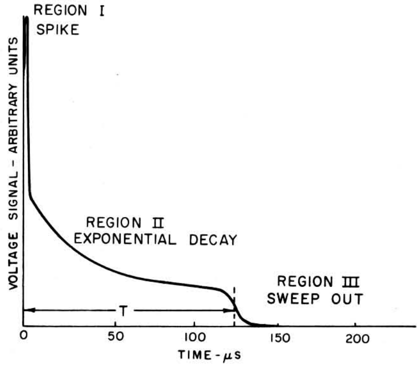


Fig. 11 - Typical oscilloscope pattern during drift time measurement.

The pulse of light generates hole-electron pairs. In spite of the movement of the holes in an electric field, the hole charge remains neutralized by electrons in order to insure space charge neutrality. Since the translating action of the junction operates on holes only, the holes are re-emitted into the germanium without their accompanying neutralizing electrons. The spike is a consequence of redistribution of electrons which takes place in order to re-establish space charge neutrality. Part of this electron current comes up from ground through the load resistance, generating the spike voltage. The size of the spike depends on the resistance of the n-type germanium between the point of absorption and emission of the holes and the load resistance. The width depends on the capacitance in the external circuit.

3.3 Interpretation of Diffusion Measurements

The results of the diffusion measurement of surface recombination (Section 3.10) can be understood on the basis of hole translation. The hole flow pattern is of the type sketched in Fig. 12. Holes feed out from the source at the focused line of light. Some recombine at the surface adjacent to the source, but a

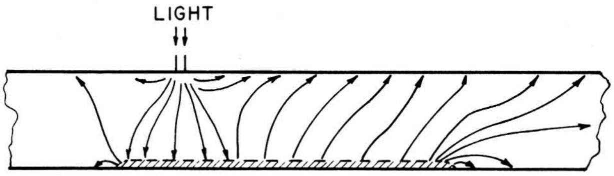


Fig. 12 - Sketch of probable hole flow pattern during measurement of lifetime by diffusion method of Fig. 5.

larger number feed into the floating junction a distance W away. These are re-emitted about uniformly over the rest of the junction, providing a region along the upper surface in which the hole density is constant with distance along the bar. Thus the measured probe voltage becomes independent of distance after an initial distance W, as in Fig. 6 until the end of the floating junction is reached. Then there is no feed-in feed-out effect and the hole density falls off with distance in just the way to be expected for a surface controlled filament lifetime, i.e.

$$\nu_s = \frac{2s}{W} \qquad \left(\text{i.e., } \tau_m = \frac{W}{2s}\right)$$

3.4 Interpretation of Diode Measurements

The same hole translation effect can take place in the measurement of effective lifetime in alloy transistor structures. After the emitter injection pulse is over, holes feed into the floating collector opposite the emitter, where the hole density is high. They immediately feed out again near the edge of the junction and so are lost to the adjacent surface. Hence this surface becomes the controlling sink, just as in the case of a diode structure without any collector. The fact that experimental agreement between diode and transistor effective lifetimes are about equal may be thus explained.

4. Conclusions

The fundamental reason for the failure of the junction analysis to predict the observed result is the assumption of a one-dimensional model. In this model the steady state hole and electron currents balance across the boundary of every point. In practice, that is, for a three-dimensional case, the total currents balance, as required for steady state conditions, but they do not necessarily balance on a per unit area basis. If lateral gradients are not the same in the surface layer and in the bulk, circulating currents can exist, which destroy the effectiveness of the layer in reducing the surface recombination. Unfortunately, the requirement for low effective surface recombination is just that $\sigma_s >> \sigma_b$, which implies that lateral conduction in the surface layer is large. This type of surface junction is therefore not suitable for reducing surface recombination in practical cases.

If it is not recognized, this effect can cause difficulty in some measurements. The measurement of lifetime in p-type germanium and in silicon by diffusion methods often yields results which are clearly too high. It is thought that this is due to the presence of layers of opposite conductivity type (inversion layer) on the surface resulting from certain etches. While careful etching apparently removes this layer from n-type germanium, we have found no certain method of removing it from p-type germanium or from n and p-type silicon. The surface layer probably acts in much the same way as the floating junction in the above experiments; minority carriers from the base semiconductor bias the measuring probe through the inversion layer, thus making the probe voltage less dependent on the distance between probe and the source of hole-electron pairs. The fact that the inversion layer is on the same surface as the probe and source, rather than on the opposite side of a thin bar as in Figs. 5 and 6 does not materially effect the argument. The pulse method of Fig. 7 and Section 3.11 is dependent only on the number of minority carriers actually within the bar and is independent of their spacial distribution, provided that the drift field is small enough to prevent sweep-out. Hence lifetime measurements on these materials are best made by the pulse drift method.

Under certain conditions, the interpretation of effective lifetime in completed transistors[8] can be affected by hole translation. If the collector does not penetrate deeply into the base wafer, the effective lifetime i simply related to the surface recombination velocity by $\tau_e = W/2s$, where W is the wafer thickness. If the collector does penetrate far into the wafer, the feed-out of holes from the edge of the collector to the adjacent free germanium surface effectively translates the recombining surface on the collector side closer to the recombining surface on the emitter side. Thus the effective thickness of the wafer is reduced. The measured effective lifetime is less in this case. When the transistor is in use as a device, however, the hole translation effect is not operative since the collector is biased in the reverse direction rather than floating as in the test measurement. The proper value of W can be determined empirically.

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