collision of a 450-Mev proton with an average nucleon in carbon. This figure is reliable only to ± 40 percent, most of the uncertainty being due to the difficulty of converting the measured differential cross sections for γ-production at 90° (4.0×10^{-29} cm^2 steradian) to a total cross section using a somewhat uncertain angular distribution. Adding to the uncertainty is the energy spread of the proton beam, which has been measured by A. H. Rosenfeld as 10 Mev and as 40 Mev at different times.

If one takes the currently popular V^0 lifetime of 3×10^{-10} second, this experiment establishes an upper limit of 7×10^{-33} cm^2 to the cross section for production of V^0's by 450-Mev protons on a nucleon in carbon.

V. CONCLUSION

It has been established with rather high probability that V^0 particles are produced in nucleon-nucleon collisions with a cross section which cannot be much greater than 10^{-32} cm^2 with an available excess center-of-mass energy of 100 Mev. Therefore, we think it possible that this energy is below the threshold for production of V particles. This probably means that they are decay products of some state which may contain two V-particles or which may contain just one particle which decays by the emission of a gamma-ray or a meson to the common V particles. Experiments at higher energy are required to investigate this problem further.

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Recombination Rate in Germanium by Observation of Pulsed Reverse Characteristic

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A new method for measuring recombination rates of minority carriers in germanium is described in which the decay of injected carriers is observed directly as a function of time. In this method the geometry is relatively unimportant as long as the sample is large in comparison to the diffusion length, and the method permits measurement of recombination rates too short to be measured with light beam methods. Data are presented which show excellent agreement between this method and a light beam method.

PREVIOUS methods for measuring recombination rates in germanium have consisted of injecting minority carriers by either a metal probe or by a beam of light, and of observing the decay of the carriers as a function of distance away from the injection probe.[1,2] These are essentially geometrical methods, measuring the diffusion length directly. As such, they have the advantage of offering a possibility for separating surface and volume effects. On the other hand, special geometries are generally required. In some cases it is advantageous to be free from restrictions on geometry, and the method to be described secures this freedom by measuring the decay of minority carriers as a function of time rather than distance.[3] Also, it will measure diffusion lengths too short to be easily measured by other means.

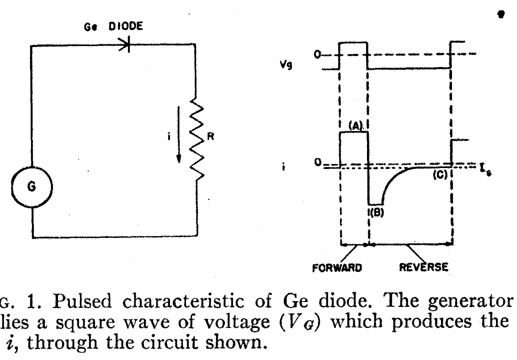

FIG. 1. Pulsed characteristic of Ge diode. The generator (G) supplies a square wave of voltage (V_G) which produces the current, i, through the circuit shown.

If a square wave of voltage is applied to a germanium diode, the resulting current will be as shown in Fig. 1, where the current at A and B is generally limited by series resistance (R) in the circuit. The current decays from the value at B to the reverse saturation current at C as the minority carriers which have been injected during the forward pulse disappear by diffusion and recombination. The shape of this decay curve can be used to determine the recombination rate.

To find the relation between the above decay curve and the recombination rate, the diffusion equation,

[1] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).

[2] L. B. Valdes and J. R. Haynes, Durham Conference on Electron Devices (June, 1951).

[3] The same results are obtainable more indirectly from the ac characteristic of rectifying junctions. See W. Shockley, *Electrons and Holes in Semi-conductors* (D. Van Nostrand and Company, Inc., New York, 1950), p. 317, and also Goucher, Pearson, Sparks, Teal, and Shockley, Phys. Rev. **81**, 637 (1951). A rough experiment by R. L. Pritchard of this laboratory indicates that the series resistance of the sample is more troublesome in the ac method than in the one described above. A recent article by Navon, Bray, and Fan, Proc. Inst. Radio Engrs. **40**, 342 (1952), describes another method for measuring τ directly, somewhat more complex in instrumentation than the above but not requiring a rectifying junction. See also M. C. Waltz, Proc. Inst. Radio Engrs. **40**, 1483 (1952), who describes a similar phenomenon in whisker diodes, but in this case considered it to be a transit time effect.

$\partial p/\partial t+(p-p_n)/\tau_p=D_p\partial^2 p/\partial x^2$,[4] must be solved as a function of time, subject to the following boundary conditions (see Fig. 2):

$$\begin{aligned} &p=0, \quad x=0, \quad t>0;\\ &p=p_n, \quad x=\infty, \quad \text{all } t;\\ &p=(p_0-p_n)e^{-x/L_p}+p_n, \quad t=0;\\ &p=p_n(1-e^{-x/L_p}), \quad t=\infty; \end{aligned}$$

where p is the density of holes; p_n is the equilibrium density of holes in the N region; $p_0=p_n \exp q\delta\phi/kT$, is the density of holes at $x=0$ with a forward bias of $\delta\phi$ volts; τ_p is the recombination time constant for holes; D_p is the diffusion constant for holes; L_p is the diffusion length for holes $[L_p=(D_p\tau_p)^{\frac{1}{2}}]$; t is time; and x is distance measured from the edge of the potential barrier. It is assumed that the thickness of the potential barrier is small in comparison to the diffusion length, that the injected carrier density is small, and that conduction across the barrier is predominantly either by n or by p carriers (the above nomenclature corresponds to conduction by holes).

The solution[5] is given by

$$p=p_n(1-e^{-x/L_p})+\frac{p_0}{2}\left\{e^{-x/L_p}\operatorname{erfc}\left[\left(\frac{t}{\tau_p}\right)^{\frac{1}{2}}-\frac{x}{2(D_pt)^{\frac{1}{2}}}\right]\right.$$
$$\left.-e^{+x/L_p}\operatorname{erfc}\left[\left(\frac{t}{\tau_p}\right)^{\frac{1}{2}}+\frac{x}{2(D_pt)^{\frac{1}{2}}}\right]\right\}, \quad (1)$$

TABLE I. Comparison of diffusion lengths as measured by the light beam method and by the decay of reverse current. The first three junctions were grown junctions (reference a) in an ingot about $\frac{1}{2}$ inch in diameter. One side was flattened for the light probe measurements. The fourth junction consisted of a Ge slab $\frac{1}{8}$ in. thick by $\frac{1}{2}$ in. diameter on which were fused In contacts (reference b); four contacts were tried, 0.02 cm, 0.04 cm, 0.05 cm, and 0.20 cm in diameter. All gave the same result. On the fourth sample, diffusion length by the light beam method was found by using an In fused contact as collector. All samples were etched in a nitric-hydrofluoric-acid-bromine etch. It was found that the rectification efficiency did not affect the results.

Conduction predominantly by	L(cm) by light beam	L(cm) by reverse characteristic	τ(μ sec) by reverse characteristic
Electrons	0.10	0.105	130
Holes	0.12	0.10	230
Electrons	0.23	0.21	500
Holes	0.17	0.18	730

[a] Teal, Sparks, and Buehler, Phys. Rev. **81**, 637 (1951).
[b] R. N. Hall, Proc. Inst. Radio Engrs. **40**, 1512 (1952).

[4] See W. Shockley, reference 3, p. 313.
[5] I am indebted to M. H. Hebb for this solution.

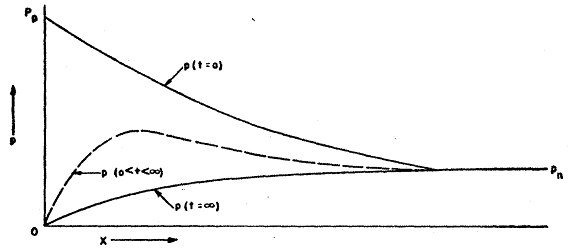

FIG. 2. Density of minority carriers as a function of distance (x) from the edge of the potential barrier for three values of time (t) after switching from forward to reverse direction of conduction.

where

$$\operatorname{erfc}x\equiv 1-\int_0^x \exp(-t^2)dt.$$

To obtain the current as a function of time, $\partial p/\partial x$ is evaluated at $x=0$; giving:

$$i=-\frac{D_pp_n}{L_p}-\frac{D_pp_0}{L_p}\left[\frac{e^{-t/\tau_p}}{2(t/\tau_p)^{\frac{1}{2}}}-\operatorname{erfc}(t/\tau_p)^{\frac{1}{2}}\right], \quad (2)$$

which for $t\gg\tau_p$ reduces to

$$i\simeq-\frac{D_pp_n}{L_p}-\frac{D_pp_0}{4L_p}\frac{e^{-t/\tau_p}}{(t/\tau_p)^{\frac{3}{2}}}. \quad (3)$$

We see, therefore, that the recombination rate, τ_p, can be obtained either by matching the decay curve to Eq. (2), or by plotting the ordinate of the decay curve multiplied by $(t/\tau_p)^{\frac{3}{2}}$ on semi-log paper. In the latter case, the slope of the straight line in the region $t\gg\tau_p$ will give τ_p directly. The interpretation will, of course, be easy only when surface recombination is small.

In Table I the recombination rate as measured by the above method is compared with that obtained by the light beam method.

If the thickness of the germanium is small relative to the diffusion length, the above boundary conditions are inapplicable. If the nonrectifying side of the Ge wafer has a high recombination rate, as it will for example if covered with Sn solder, the current falls off in accordance with $i=k_1+k_2\exp(-D_p\pi^2t/W^2)$, where W is the thickness of the Ge. If the side away from the rectifying junction has a very low recombination rate, as is usually the case in In-Ge-Sb diodes, the dependence will be $i=k_3+k_4\exp(-D_p\pi^2t/4W^2)$. Both of these have been checked experimentally.

I wish to thank R. N. Hall for the samples used in this investigation and for the use of apparatus to measure recombination rate by the light beam method.