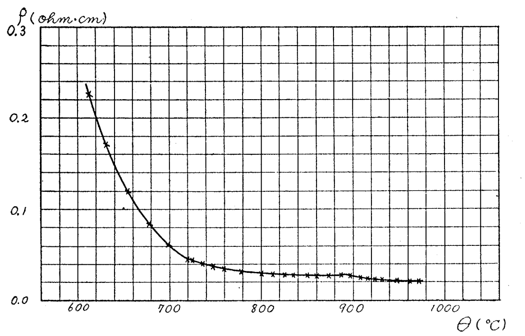

FIG. 2. Specific resistance *vs* temperature.

The dc resistance of ceramic samples was measured by the usual potentiometer method. Figure 2 shows the specific resistance measured in cooling as a function of temperature, in which a slight maximum and a break are seen near 890°C and 720°C, respectively. Further, it is notable that the specific resistance increases slowly with decreasing temperature above 720°C, although it increases exponentially below this temperature as in the usual semiconductors.

Kehl *et al.*[1] and Wyart and Foëx[4] did not observe any change of crystal structure near 910°C. Our measurement of lattice constants by the powder photograph method, however, revealed that, in heating, both the *a* and *c* axes, and therefore *v* (the lattice volume), increase slightly near this temperature, although the crystal system does not change.

The author wishes to thank Professor T. Muto for his kind criticism and advice.

[1] Kehl, Hay, and Wahl, J. Appl. Phys. **23**, 212 (1952).
[2] M. Foëx, Compt. rend. **220**, 917 (1945).
[3] Sawada, Ando, and Nomura, Phys. Rev. **84**, 1054 (1951).
[4] J. Wyart and M. Foëx, Compt. rend. **232**, 2459 (1951).

Effect of Transit Time on Ge Rectifier Behavior*

R. BRAY AND B. R. GOSSICK
Purdue University, Lafayette, Indiana
(Received June 8, 1953)

THE phenomenon of hole-injection and consequent conductivity-modulation[1] is the main factor responsible for the low spreading resistance in the forward direction of the high back voltage (hbv) Ge point contact rectifiers. Long lifetimes and transit times associated with this effect are responsible[2] for the well-known decrease in rectification efficiency of these rectifiers at high frequency. Their frequency dependence was first investigated in detail by Yearian,[3] who measured the rectified dc current output as a function of sinusoidal ac voltage for frequencies up to 60 Mc/sec. Deviations from low-frequency behavior became noticeable at 100 kc/sec, with the current output becoming steadily smaller with increasing frequency. Relatively, the deviations were greatest for voltages above 0.6-volt rms, suggesting that the frequency-dependent element was the spreading resistance.

There is less injection and consequently higher forward resistance at high frequency when the period of the forward swing is shorter than the transit time of the injected holes through the spreading resistance region, or shorter than the lifetime if that is the smaller quantity. To investigate the magnitude of the transit times involved in such effiects, forward $I-V$ characteristics of hbv Ge rectifiers were measured under very fast pulse conditions. At the beginning of the pulse (rise time ~0.007 μsec) the resistance was much higher than at the end of the pulse (0.4 μsec later), as illustrated in Fig. 1. The characteristic at the later time is inseparable from the dc characteristic, indicating that transit times of less than 0.4 μsec are involved. Even at the beginning of the pulse, the resistance was already changing rapidly, so that the observed value need not represent the maximum attainable forward resistance. In $p-n$ junction rectifiers, the bulk resistance contribution to the forward characteristic is not concentrated near the barrier, and resistance changes accordingly occur over longer time intervals. This is illustrated in Fig. 2 by forward $I-V$ characteristics for a $p-n$ junction. At the end of a 3.6μsec pulse the resistance is still much higher than at dc. In fact, little change occurs during the pulse interval. Figure 2 also shows the characteristic of the same junction at liquid nitrogen temperature. Pulse (0.2μsec) and dc measurements are indistinguishable. The implication drawn here is that the lifetime is very small at the low temperature, thereby severely limiting the depth of penetration of injected carriers and the conductivity modulation.

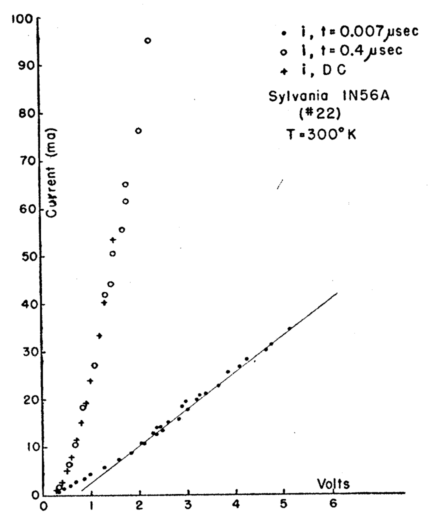

FIG. 1. Comparison of forward current-voltage characteristics of a high back voltage Ge point contact rectifier at beginning and at end of a pulse, and at dc.

The reverse current of a hbv Ge rectifier would ordinarily have negligible influence on the dc rectified current produced by an ac signal. However, at high frequency, the holes injected during the forward swing, may be brought back and collected by the same contact during the reverse swing.[2] This may be called a "self-

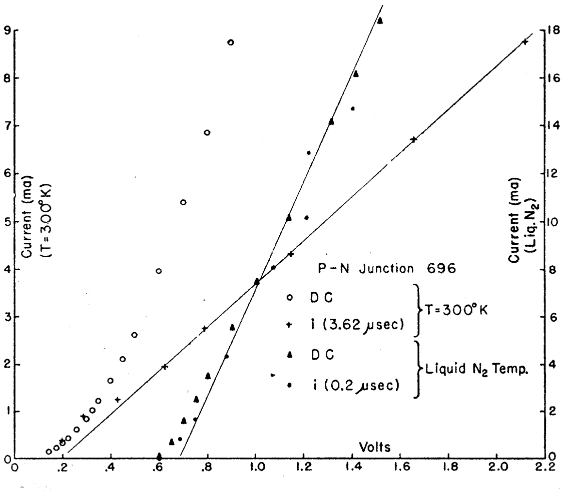

FIG. 2. Comparison of pulse and dc forward current-voltage characteristics for a $p-n$ junction at $T=300$°C and at liquid N$_2$ temperature.

transistor" action. The condition for this to occur is that the period of the high frequency be of the order of or smaller than the lifetime of the injected carriers. It was observed already by Yearian[3] and co-workers that the reverse resistance of hbv Ge rectifiers was decreased at 30 Mc/sec if there was forward swing to the ac voltage. When precautions were taken to eliminate any forward swing, the reverse resistance and peak-back voltage were found to be even higher at 30 Mc/sec than at 60 cps. Michaels and Meacham,[4] using pulse techniques, have observed relatively high pulses in the reverse direction corresponding to rapid collection of holes stored in the germanium during the forward pulse. Investigations of special aspects of this return pulse have been reported by Waltz,[5] Pell,[6] Schulman,[7] and Gossick.[8]

---

* Part of this work was done with the support of the Signal Corps.

[1] See W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 99.

[2] R. Bray and H. J. Yearian, Phys. Rev. **77**, 760 (1950).

[3] H. J. Yearian, *Resistance of High Back Voltage Germanium on Voltage and Frequency*, National Defense Research Committee Report, NDRC 14-581, Purdue University, Oct. 1945 (unpublished). See also H. C. Torrey and R. M. Whitmer, *Crystal Rectifiers* (McGraw-Hill Book Company, Inc., New York, 1948), p. 378.

[4] L. A. Meacham and S. E. Michaels, Phys. Rev. **78**, 175 (1950).

[5] M. C. Waltz, Proc. Inst. Radio Engrs. **40**, 1483 (1952).

[6] E. M. Pell, Phys. Rev. **90**, 278 (1953).

[7] R. G. Shulman and M. E. McMahon, Hughes Aircraft Company Report, 1953 (unpublished).

[8] B. R. Gossick, following Letter [Phys. Rev. **91**, Aug. 15 Letter (1953)].

Post-Injection Barrier Electromotive Force of $p-n$ Junctions*

B. R. Gossick
Purdue University, Lafayette, Indiana

(Received June 8, 1953)

EXPERIMENTAL studies of the transient behavior of germanium rectifiers have been made by many investigators.[1-8] The resistance with a voltage applied in the blocking direction is normally very high. However, if the rectifier has been drawing forward current the initial back resistance is low; even without an applied voltage in the back direction there is a transient reverse current. This transient reverse current results from an emf developed by the barrier, due to nonequilibrium carrier concentrations at the junction barrier.

By injecting carriers across a $p-n$ junction with a high back voltage (hbv) point contact diode in series, the post injection barrier emf may be observed under approximately open-circuit conditions. The back pulse of the diode is so short compared to that of a $p-n$ junction that it acts effectively as an ideal rectifier. The barrier emf following injection is given, according to Fan,[9] by

$$V=-\frac{kT}{e}\ln\frac{p_n p_{p0}}{p_{n0}p_p}, \tag{1}$$

where p_n and p_p represent the hole concentrations on the n and p sides of the junction, respectively, the equilibrium concentrations being denoted by the subscript 0. Assuming that the following inequality holds:

$$\frac{p_n}{p_{n0}}\gg\frac{p_p}{p_{p0}}, \tag{2}$$

then (1) may be approximated by

$$V=-\frac{kT}{e}\left(\ln\frac{\Delta p_n}{p_{n0}}-\frac{t}{\tau_p}\right), \tag{3}$$

where τ_p refers to the lifetime of minority carriers and Δp_n to the initial increase of p_n. The response V may be similarly derived in terms of electron concentrations. The observed response patterns are of the shape indicated by (3), except near the very end of the post injection pulse where (2) is no longer satisfied. Figure 1 shows two oscilloscope patterns of the terminal emf across a $p-n$ junction after injection through a CK708 diode.

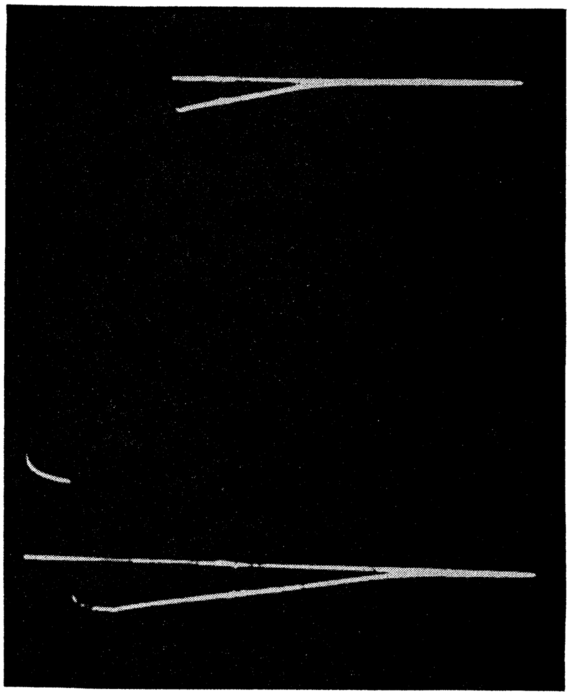

FIG. 1. Oscilloscope patterns of terminal emf after injection.

	Upper pattern	Lower pattern
Injection time	0.35 μsec	3.6 μsec
Initial height of back pulse	0.1 volt	0.2 volt
Lifetime calculated from slope using (3)	3.5 μsec	3.5 μsec

Trailing edge of the injection pulse causes rounding of the front edge of the back pulse in the lower pattern.

The initial amplitude of the barrier emf is determined by the final potential drop across the barrier during injection, because the potential difference across the junction is determined by the carrier concentrations on the two sides, which are unable to change instantaneously at the termination of injection. When current is

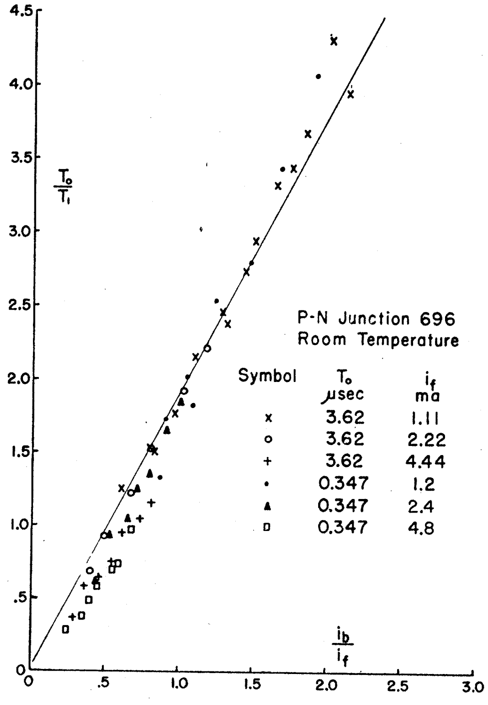

FIG. 2. T_0/T_1 *vs* i_b/i_f.