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on Voltage and Frequency*, National Defense Research Committee Report, NDRC 14-581, Purdue University, Oct. 1945 (unpublished).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[7] R. G. Shulman and M. E. McMahon, Hughes Aircraft Company Report, 1953 (unpublished).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*

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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.

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

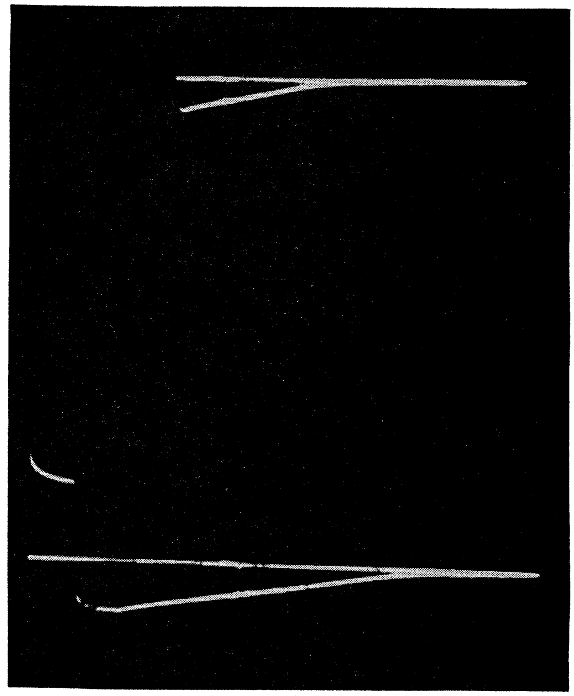

FIG. 1. Oscilloscope patterns of terminal emf after injection.

	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.

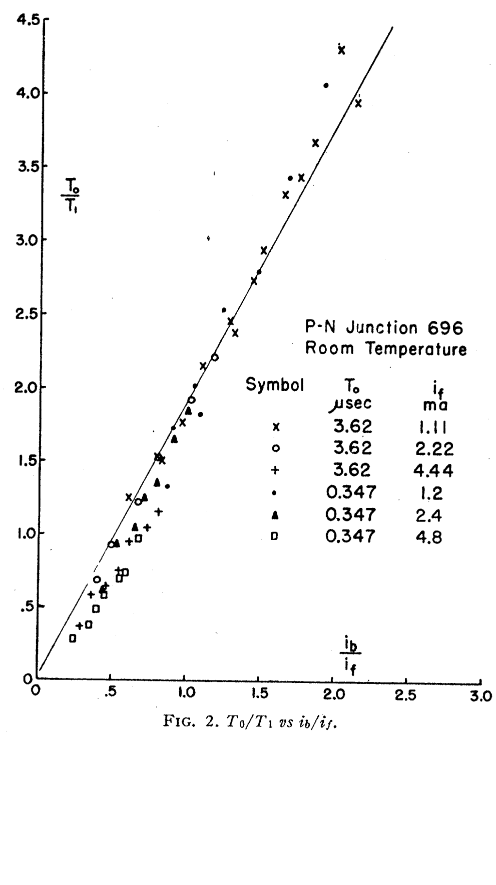

FIG. 2. T_0/T_1 vs i_b/i_f.

permitted to flow, the injected minority carriers drift back to the junction where their concentration becomes depleted with time, since more carriers drift away on the side of the junction where they are the majority carriers. Thus in time the flow of injected carriers back to the junction will be enhanced by diffusion. Experiments were made on a sample with constant cross section, the p and n regions being long compared to the injection distance. It was observed that the back current remains essentially constant over a considerable time T_1. Consequently, the calculated voltage drop across the junction and therefore the injected carrier concentration at the junction must have been roughly constant during this time.[10] With a small series resistance the trailing edge of the pulse is sharp and a definite value of T_1 can be assigned. With T_1, and the forward rectangular pulse length T_0, small compared to the carrier lifetime we should have, approximately,

$$T_0/T_1 = i_b/i_f, \tag{4}$$

where i_f and i_b refer to injection and collection current, respectively. Figure 2 is an experimental plot of T_0/T_1 *vs* i_b/i_f, indicating that about half the injected carriers were returned during T_1.

* This work was supported by Signal Corps contract. The author is indebted to K. Lark-Horovitz and H. Y. Fan for discussions.

[1] H. Yearian, work summarized in *Crystal Rectifiers* by H. C. Torrey and R. M. Whitmer (McGraw-Hill Book Company, Inc., New York, 1948).
[2] R. Bray and H. Yearian, Phys. Rev. **77**, 760 (1950).
[3] R. Bray, Ph.D. Thesis, Purdue University, June, 1949 (unpublished).
[4] P. R. Bell (private communication).
[5] S. E. Micheals and L. A. Meacham, Phys. Rev. **78**, 175–176 (1950).
[6] M. C. Waltz, Proc. Inst. Radio Engrs. **40**, 1483 (1952).
[7] R. G. Shulman and M. E. McMahon, Hughes Aircraft Company Report, 1953 (unpublished).
[8] E. M. Pell, Phys. Rev. **90**, 278 (1953).
[9] H. Y. Fan, Phys. Rev. **75**, 1631 (1949).
[10] The calculated emf's are in the neighborhood of 0.2 volt at room temperature and 0.65 volt at liquid nitrogen temperature for the sample used to obtain data for Fig. 2.

Thermoluminescence of Quartz and Fused Quartz Colored by X-Ray Irradiation

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(Received June 3, 1953)

THE study of color centers in quartz and fused quartz induced by x-ray irradiation has been studied by the writer.[1] When x-rayed quartz and fused quartz are heated, luminescence is observed and the absorption bands are bleached.

We prepare fused quartz by two methods, in one of which fused quartz is produced in a strongly reducing condition and in the other in a mildly oxidizing condition.

The samples of quartz and fused quartz (10×10×0.3 mm) were exposed to x-rays (100-kv, 3-ma, tungsten target) at room temperature for 56 hours. Saturation of coloration takes place approximately after exposure for 56 hours.

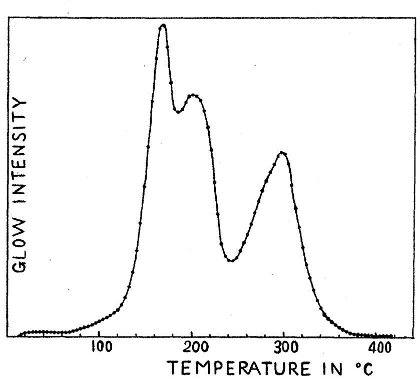


FIG. 1. Glow curve of quartz.

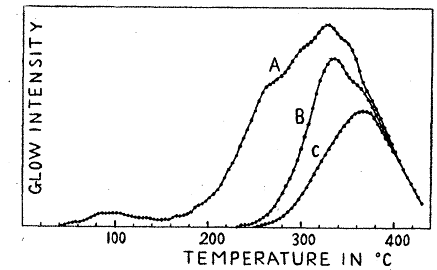


FIG. 2. Glow curves of fused quartz prepared in a reducing condition. (A): no decay; (B): 15-min decay at 276°C; (C): 5-min decay at 312°C.

The emitted light was observed with a multiplier phototube of RCA 1P28 type connected to a string electrometer. Glow curves were obtained at a linear heating rate of 0.033°C/sec, which is so slow that a good resolution in glow curves is obtained.

Figures 1, 2(A), and 3(A) give examples of glow curves for quartz and fused quartz. These curves are reproducible in general shape.

A comparison of the glow curves for quartz and fused quartz shows that in quartz crystal there exist trapping centers having

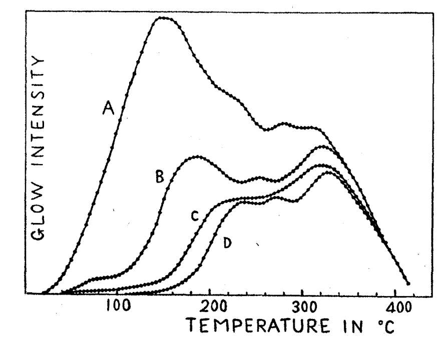


FIG. 3. Glow curves of fused quartz prepared in a mildly oxidizing condition. (A): no decay; (B): 10-min decay at 150°C; (C): after B decay, a further 5-min decay at 196°C; (D): after B decay, a further 10-min decay at 196°C.

several discrete trapping levels, but in fused quartz there exist some groups of trapping levels.

To verify the above, the following experiment was performed. A glow curve for traps of one depth has the same shape and peak temperature regardless of the number of electrons trapped. Figures 2 and 3 show glow curves of fused quartz prepared in a reducing condition and in a mildly oxidizing condition, respectively, after various periods of decay at different temperatures. Fused quartz was x-rayed and then allowed to decay for the designated

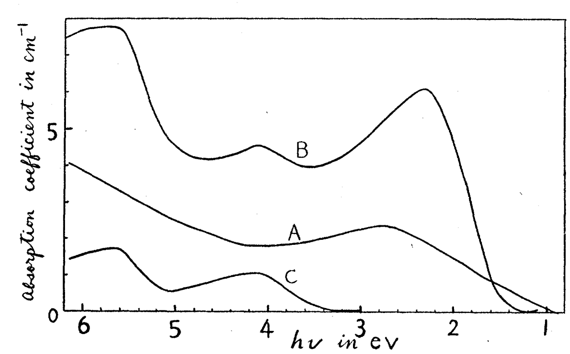
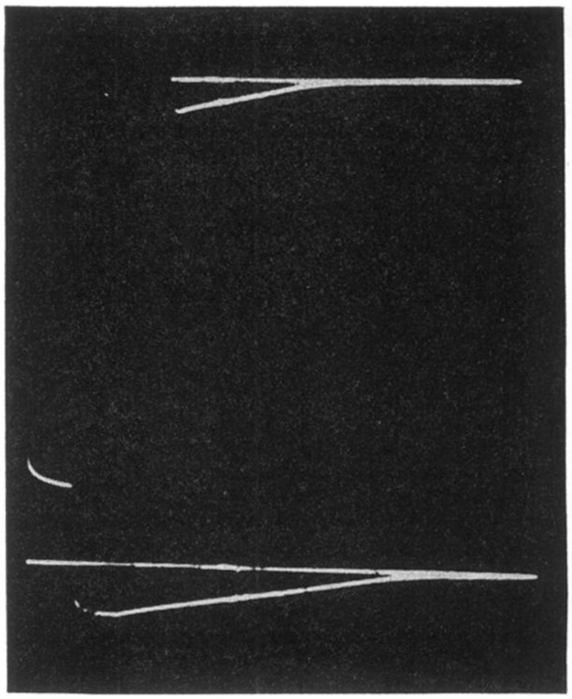


FIG. 4. Induced absorption bands of quartz and fused quartz (A): quartz; (B) and (C): fused quartz prepared in the reducing and mildly oxidizing conditions, respectively.



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