eter to the temperature of the surface of the bath. Temperature gradients simply cannot be supported in the superfluid bath. Indirectly the shift in the resistance of the carbon thermometers was a measure of the height of the helium level. Observing the height of the level through the clear windows of the Dewar flasks made it clear that the actual level of the carbon thermometers was effectively raised to about 5 cm above the bottom of the brass apparatus because of the high heat conductivity of the brass metal.

APPENDIX III

Suppose that not all of the power, E_1, produced in plate P_1 went to the plate P_0, but that a small quantity, e, went to the guard ring because of a temperature difference T_2-T_1. The error caused by this heat flux will be minimized as the distance of separation of the plates P_1 and P_0 vanishes. To see this let us define the thermal resistance of the path between P_1 and the guard ring as "r," such that:

$$r=(T_2-T_1)/e. \tag{9}$$

The ratio of the power, e, which goes to the guard ring to the power, E_0, which goes to the plate P_0 will then be:

$$e/E_0=[(T_1-T_2)/r]\times[R/(T_1-T_0)]. \tag{10}$$

As the thermal resistance R of the helium column between P_1 and P_0 vanishes with the distance $d=0$, we may conclude that the ratio becomes small and that the relative importance of the small heat leak to the guard ring is minimized. The apparatus was constructed in such a way as to make the thermal resistance, r, as large as possible.

TABLE II. Comparison of results on heat conductivity.

T°K	$10^5\times K$(exp) cal/deg cm sec	K Keesom	K Sound absorb.	$2.5c_v\eta$ Elementary gas theory	K_0 Zero resistance
2°.24−	4.8				4.05
2°.24+	4.4			3.7	4.15
2°.30	4.6+		100		4.4
2°.38	4.6−				4.35
2°.45	4.4				4.4
2°.50	4.6			3.2	4.6
2°.58			17		
2°.86	4.9 5.2				5.2 5.3
3°.08			5.5	3.3	
3°.35	5.1 5.7	6	6		5.4 5.3
3°.50			7	3.6	
3°.63	6.4		6.7		5.6 6.1
4°			5.5	4.4	
4°.2	6.1 6.3		5		6.4 6.6

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Injected Light Emission of Silicon Carbide Crystals

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Recombination of carriers injected through $P-N$ boundaries in silicon carbide crystals may lead to light emission ("injected light emission"). This light emission was investigated as a function of temperature and of current through the crystal by use of a photomultiplier. The emission spectrum extends from 4500A to 6500A at room temperature and is found to be nearly independent of current from 0.1 ma to 50 ma. The light intensity increases approximately proportionally to current (efficiency about 10^{-6} quanta per electron at room temperature for a particular crystal).

I. INTRODUCTION

SOME silicon carbide crystals emit "cold" light while current passes.[1-7] Two types have been reported: (a) a bluish light and (b) a yellow light, the type emitted depending on the direction of current flow. The parts of the crystal that emit yellow light do not coincide, in general, with those emitting blue light on current reversal; nor does the same crystal necessarily emit both types. We conclude that the mechanism of excitation differs for the two cases.

Previously published data on the intensity and spectral distribution of the light are of a qualitative nature. In this paper quantitative information is presented on the spectral distribution of the yellow light and its dependence on current density and temperature.

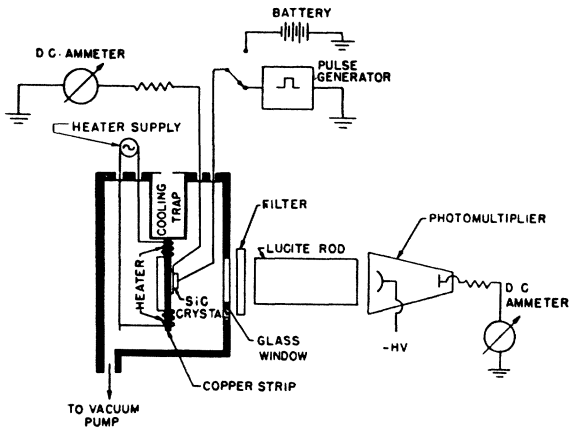


FIG. 1. Experimental arrangement for measurement of the light emission from silicon carbide crystals.

[1] O. Lossew, Wireless World and Radio Review **271**, 93 (1924).
[2] O. Lossew, Z. Fernmeldetechnik **7**, 97 (1926).
[3] O. Lossew, Phil. Mag. **6**, 1028 (1928).
[4] O. Lossew, Physik. Z. **30**, 920 (1929).
[5] O. Lossew, Physik. Z. **32**, 692 (1931).
[6] O. Lossew, Physik. Z. **34**, 397 (1933).
[7] B. Claus, Ann. Physik **11**, 331 (1931).

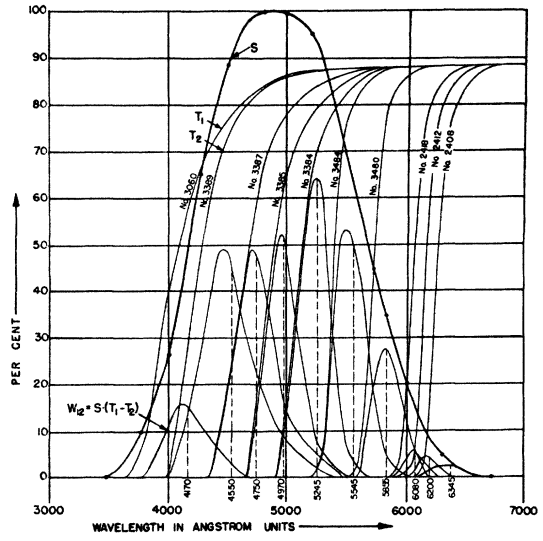


FIG. 2. Transmissivity "T" of Corning Glass Filters (No. of filter indicated in figure), photomultiplier No. 5819 sensitivity "S," and correction factor $W=S(T_1-T_2)$ as functions of wavelength.

An explanation is proposed for the mechanism of the yellow light emission.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown diagramatically in Fig. 1. The current source for the crystal consisted of either a battery or a pulse generator. The silicon carbide crystal was silver-plated on one side and attached by silver paste to a brass plate mounted on a copper strip extending from a Kovar coolant container. Two heating coils insulated by mica from the copper strip permitted measurements at elevated temperatures. The light emission was studied under vacuum to prevent water condensation at low temperatures. The light was guided by a Lucite rod to an RCA 5819 photomultiplier tube. The spectral response of the photomultiplier was calibrated against a thermopile by using a prism monochromator. The relative sensitivity curve of the photomultiplier is shown in Fig. 2 (curve S). Its maximum sensitivity was

$$S_{\max}=14{,}900\ \mu\text{amp}/\mu\text{watt}$$

for a wavelength of 4800A. In Fig. 2 the transmissivities (e.g., curves T_1, T_2) are shown for various Corning glass filters. These were inserted between crystal and photomultiplier in order to determine the spectral distribution of the emitted light. The bell-shaped curves are the differences between the transmissivities of two successive filters multiplied by the photomultiplier sensitivity, e.g., $W_{12}=S(T_1-T_2)$.

The following procedure was used to calculate the light intensity per unit wavelength from the photomultiplier readings. Let the reading with filter 1 inserted be I_1, and with a filter 2 be I_2. The average light energy per unit wavelength in the range of W_{12} is then

$$E_\lambda=\left[(I_1-I_2)\Big/\int S(T_1-T_2)d\lambda\right]\cdot f/S_{\max}. \quad (1)$$

(f is a numerical factor of the order of 10 resulting from the geometry of the optical arrangement). The application of Eq. (1) is justifiable if E_λ does not change much over the range of the integration. E_λ is the spectral density of the emitted light at the value of λ which halves the area of W_{12}. The values of λ so chosen for each of the bell-shaped curves are indicated by dotted lines in Fig. 2.

TABLE I. "Efficiency" and threshold current for three temperatures. The "efficiency" is defined as the ratio of the photomultiplier current to the crystal current in excess of the threshold current.

Temperature	25°C	−45°C	−150°C
"Efficiency"	0.45×10^{-3}	1.0×10^{-3}	$2.5\times10^{-}$
Threshold current for light emission from the crystal	325 μa	190 μa	40 μa

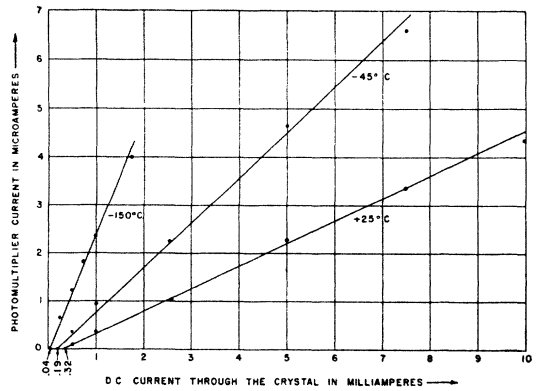


FIG. 3. Photomultiplier current as a function of the crystal current for various temperatures. The photomultiplier current is proportional to the intensity of the light emitted from the crystal.

The silicon carbide crystals obtained through the courtesy of the Carborundum Company were grown in a commercial pile. The crystals used were bluish in color and had a surface oxide layer which was removed by etching with hydrofluoric acid.[8] Emitting areas were found by placing the crystal on a brass plate and probing the surface with a point contact 22 volts negative with respect to the plate. The crystals passed currents of the order of 10 ma at this voltage. Suitable crystals were silvered by evaporation and then mounted on the brass plate with silver solder or silver paste. In some cases the base of the crystal was coated with zirconium by heating zirconium hydride in contact with the crystal in vacuum. Silver soldering to the zirconium layer is possible.[9]

[8] H. G. Heine and P. Scherrer, Helv. Phys. Acta **13**, 489 (1940).

[9] C. S. Pearsall and T. K. Zingeser, *Metal to Non-Metallic Brazing* (Research Laboratory of Electronics, M.I.T., April 5, 1949), Technical Report 104 (unpublished).

III. EXPERIMENTAL RESULTS

In this paragraph observations on a particular crystal are described. The light intensity varies approximately linearly with current above a certain threshold current (see Fig. 3). Values of the threshold current and of the "efficiency" (defined as the ratio of the photomultiplier current to the crystal current in excess of the threshold current) are listed in Table I for three temperatures. "Efficiency" of the light emission is not very sensitive to change in temperature. Shift in "efficiency" with temperature is due in part to a change in the spectral distribution of the emitted light. This has to be taken into account along with the sensitivity of the photomultiplier to obtain the absolute efficiency. No light was emitted from this particular crystal upon reversal of current.

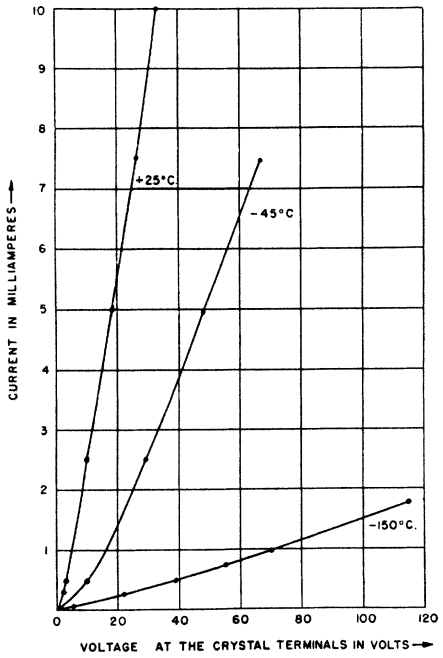


FIG. 4. Current-voltage characteristic at various temperatures.

The curves of Fig. 3 may be translated into curves giving the photomultiplier current as a function of the voltage applied to the crystal by means of the current-voltage characteristic given in Fig. 4. The choice of current as the independent variable in Fig. 3 was made for the following reason. The voltage measured between the electrode of the crystal is the sum of the voltage drops at various parts of the crystal and the electrode contacts. The light emission occurred around the cats-whisker contact in a zone of about 1 mm diameter and of limited depths. Thus the voltage at the light emitting layer was only a fraction of the voltage between the electrodes, whereas the current given in Fig. 3 was actually flowing through the light emitting layer.

The spectral distribution of the emitted light was investigated with filters, as described previously. Figure

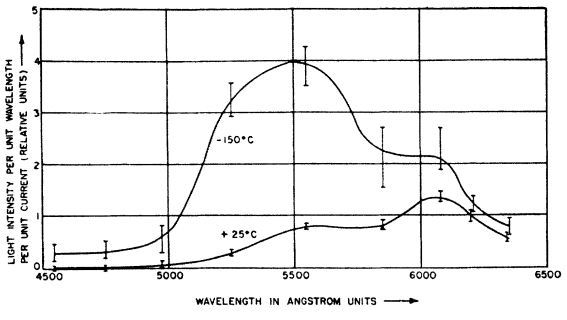


FIG. 5. Light intensity per unit wavelength per unit current as a function of wavelength at 25°C and −150°C. The spread of the values obtained for various currents is indicated in the figure.

5 shows the spectral distribution at room temperature and −150°C. Each curve is the average of about 5 measurements at various current densities. Most of the light emission at room temperature occurs between 5000A and 6500A with a maximum at 6100A. At −150°C, there is a maximum at about 5500A. On the basis of the multiplier sensitivity, an efficiency at room temperature of 10^{-6} light quanta emitted per electron passing was calculated for this particular crystal.

It should be pointed out that the spectral emission curves may vary to a certain extent from crystal to crystal. This was to be expected, since the light comes from zones of various depths and is therefore subject to the filter action of silicon carbide layers of various thicknesses. Also, the transparency of the crystals was influenced by their particular impurity content.

Figure 6 shows the difference between the multiplier currents for two consecutive filters divided by the read-

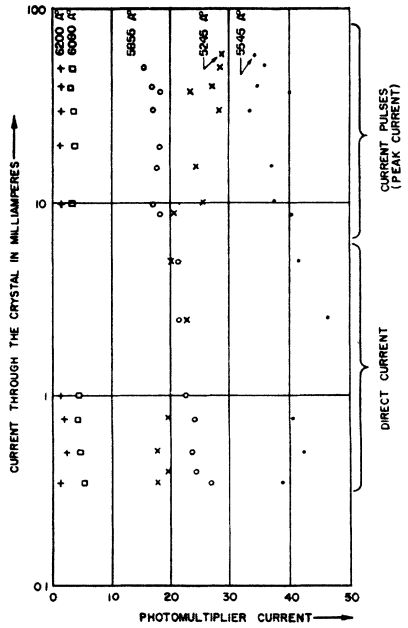


FIG. 6. Light emission in a given wavelength range as function of the current through the crystal.

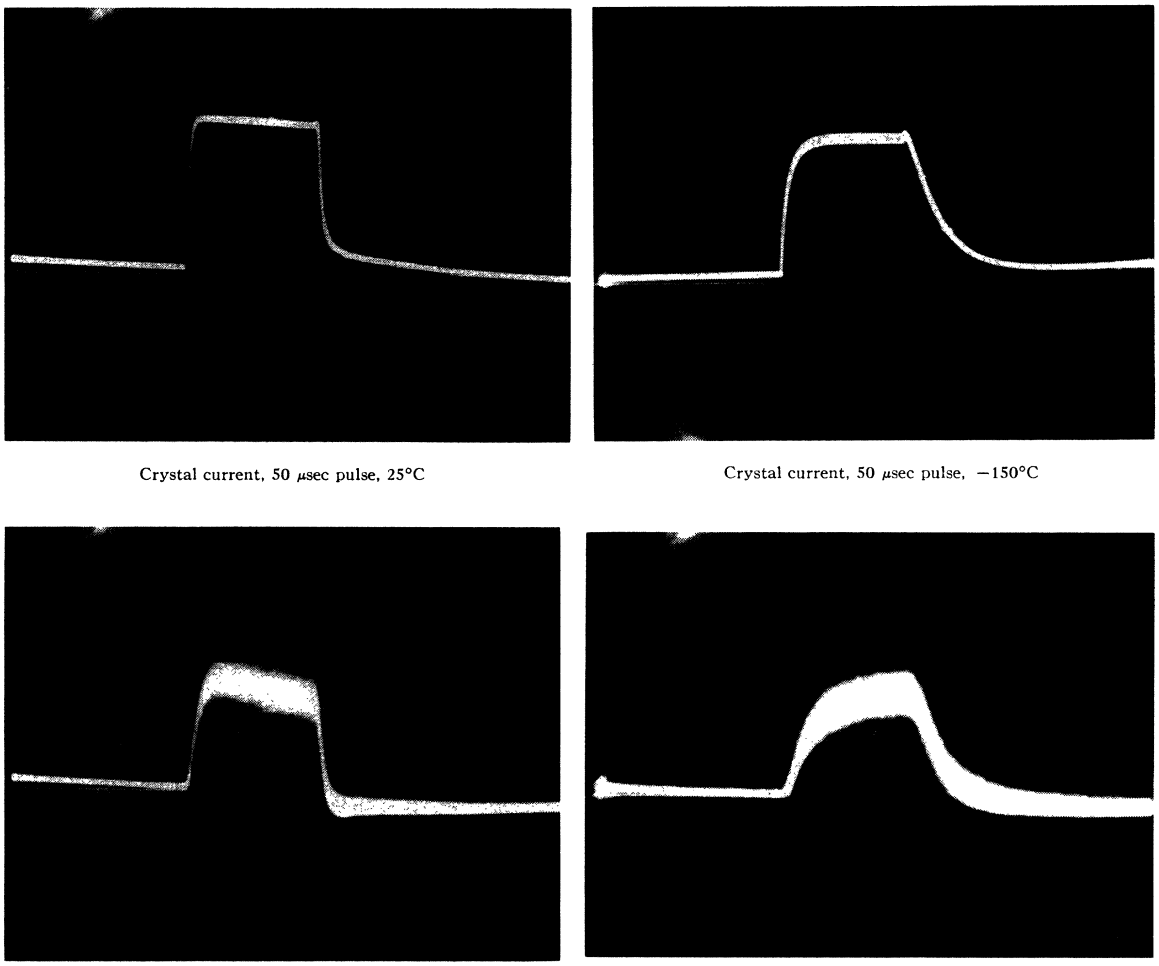


FIG. 7. Light response of silicon carbide to an applied current pulse.

ing without filter,[10] $(I_1-I_2)/I_0$, as a function of the current through the crystal at room temperature. In order to decrease heating of the crystal, current pulses of repetition rate 200 cycles/sec and 50 microseconds duration were used at the higher currents. Figure 6 shows that the spectral distribution changes only slightly with current density.

Figure 7 compares the wave shape of a current pulse through the crystal with that of the emitted light pulse showing high fidelity up to the megacycle range at both room temperature and −150°C. The features of the silicon carbide light emission which are most promising for possible applications are the linear dependence of emitted light intensity on current, and the high frequency response of the light emission.

[10] I_0 is taken to be 10 percent less than the value of the intensity measured in the absence of a filter. This correction is introduced to take into account the reflection losses present with a filter inserted.

IV. ON THE MECHANISM OF THE LIGHT EMISSION

In the early literature the light emission was related to the presence of an "active layer" on the surface of the crystal. Lossew removed the "active layer" by grinding and measured the resistance between two probes placed on the surface at various intermediate stages of the grinding process.[6] The resistance was found to increase by several orders of magnitude with progressive removal of material and then to drop sharply after 12 microns had been removed. Probing the potential distribution while current was passing from the surface into the crystal showed the presence of a rectifying junction at the boundary of the active layer and the bulk silicon carbide. Yellow light emission occurs when the current passes through the boundary in the forward direction. In a later paper[11] it is mentioned that the active layer consists of an N-type layer, whereas the bulk consists of P-type material.

[11] O. Lossew, Compt. rend. acad. sci. U.R.S.S. **29**, 363 (1940).

We have investigated the potential distribution over the surface of a crystal in the neighborhood of a "catwhisker" passing current both in the blocking and the forward directions. When the "catwhisker' was made negative, light was emitted from a well-defined area around it. This polarity characterized the forward direction of the current flow. No pronounced inhomogeneity of the potential distribution was found at the boundaries of the light emitting area with the current flowing in the forward direction. When the direction of current was reversed ("catwhisker" positive), the yellow light emission disappeared. However, there was a pronounced potential drop along a certain line. This line was found to coincide with the boundary of the light emitting zone when current passed in the forward direction. The observed potential distribution can be explained by assuming the bulk of the crystal to be P-type with an N-type surface layer. When current passes in the blocking direction, the N-type layer is separated by a highly blocking $P-N$ barrier from the bulk of the crystal and acts therefore like an equipotential electrode.

On some crystals it was observed that the yellow light emission did not occur from a well-defined area around the point contact, but rather from a small region in which the intensity decreased with increasing distance from the point. This may be ascribed to a rather low conductivity in the N-type layer. It may be, however, that the light emission is not connected with a $P-N$ barrier in some of these cases but rather with a metal-semiconductor barrier. In all cases, the yellow light emission was observed with current passing in the forward direction.

The light emission has been attributed to the bremsstrahlung of electrons.[12,13] This theory does not explain the fact that the spectral distribution is nearly independent of the applied field strength. We propose that the light is emitted as a result of recombination of carriers injected across barrier layer by a voltage in the forward direction (Fig. 8). Figure 8 shows the energy level diagram of a $P-N$ type boundary. On one side of the barrier, conduction is due predominantly to electrons, on the other, conduction is due predominantly to holes. A voltage applied to the barrier layer in the forward direction drives both the electrons and the holes toward the barrier and at the same time lowers the height of the barrier. This may lead to an injection of electrons and holes across the barrier as is known from studies of the transistor effect.[14] The injected carriers (holes in the N-type part, electrons in the P-type part) disappear with increasing distance from the barrier due to recombination. In the recombination process an amount of energy equal to the width of the forbidden band of the silicon carbide is released.[15] This energy can be either emitted as light or dissipated as heat (lattice vibration). We have no detailed knowledge whether the recombination process leading to light emission in silicon carbide takes place at impurities (activators), lattice defects, or at the surface. The emission band of the silicon carbide is located at a slightly longer wavelength than the absorption edge ($\lambda_0=0.44$ micron at room temperature) of the silicon carbide lattice. Thus, the energy of the emitted light quanta is somewhat smaller than the forbidden band width, $hc/\lambda_0=3$ electron volts, of the silicon carbide lattice.

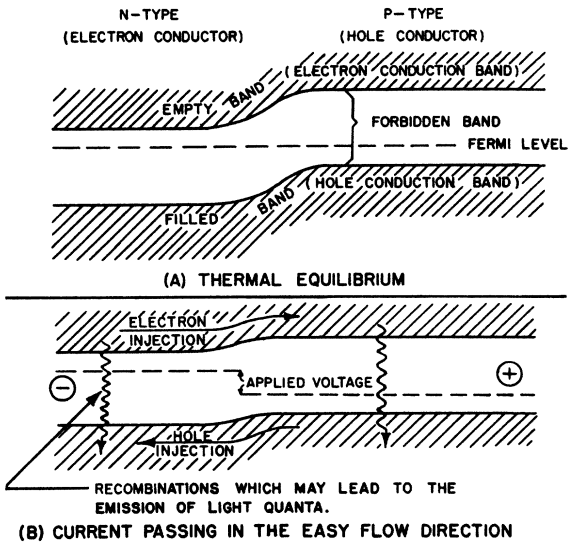
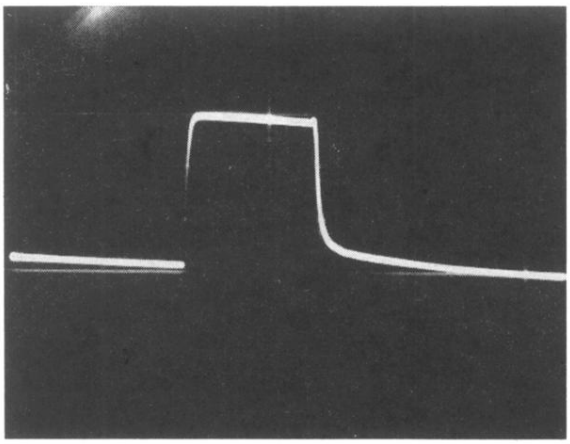


FIG. 8. Energy diagrams for a $P-N$ boundary. The recombination of electrons and holes that leads to light emission may occur at impurities (activators).

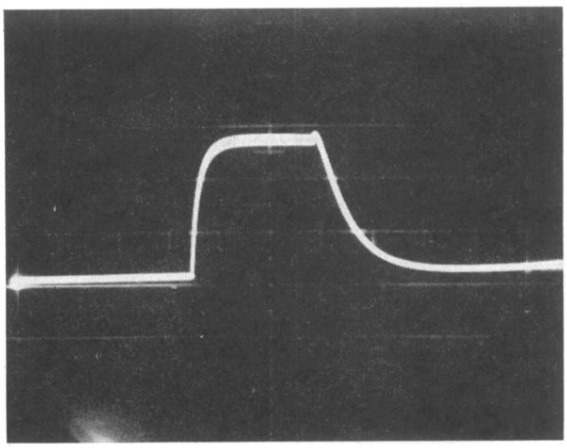
The luminescence from silicon carbide crystals under current flow as compared with that of phosphors under x-radiation, uv-radiation, or electron bombardment differs in the mechanism of the excitation process rather than of the emission process. Electrons in excited states are necessary for any case of light emission. In phosphors recombination takes place in the same locality where the electrons are excited. In the case of silicon carbide light emission, electrons are injected into the elevated energy states from distant parts of the crystal ("injected light emission"). This difference between phosphor light emission and injected light emission is analogous to that between photoconductivity and the increased conductivity due to carrier injection.

Acknowledgment is made to Dr. W. Ramm and Mr. J. Rothstein for valuable discussion, and to Mr. E. L. Geissinger for some of the preliminary measurements.

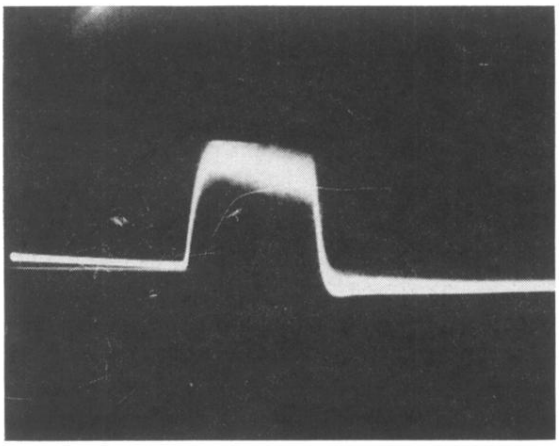
[12] O. Lossew, Physik Z. **32**, 695 (1931).
[13] B. Claus, Ann. Physik **11**, 331 (1931).
[14] For a review of the work on transistors see W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950).
[15] The forbidden band width may be identified with hc/λ_0 for structures of the diamond type, as has been proved for germanium and silicon from considerations of the optical absorption and intrinsic conduction.



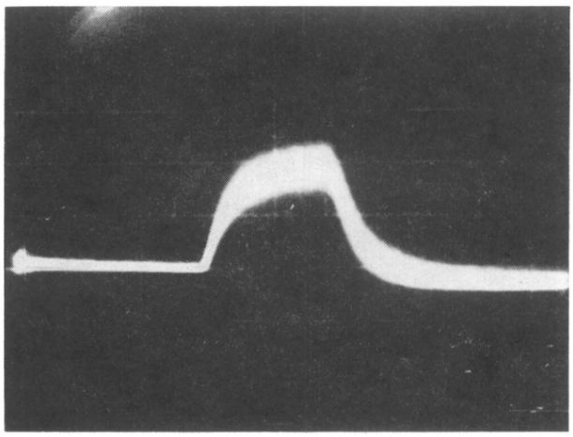
Crystal current, 50 μsec pulse, 25°C



Crystal current, 50 μsec pulse, −150°C



Photomultiplier current, 25°C



Photomultiplier current, −150°C

FIG. 7. Light response of silicon carbide to an applied current pulse.