A New Germanium Photo-Resistance Cell

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June 27, 1949

The various photoelectric properties of the semi-conductor germanium have been studied by a number of investigators. Bray and Lark-Horovitz[1] observed both photo-conductive and photo-e.m.f. effects in germanium crystal rectifiers. Benzer has observed a "photo-diode" effect[2] due to the illumination of an N-P barrier in series with a rectifying contact, and has studied both the photo-behavior of rectifying germanium-to-metal contacts in the presence of applied bias voltages[3] and the rectification behavior of such contacts in the presence of light.[4] The spectral response and quantum efficiency of the photo-e.m.f. effect at N-P boundaries in germanium were determined by Goucher.[5]

The purpose of the present letter is to report a device utilizing a photo-conductive property of germanium which combines high spatial resolving power with an over-all quantum efficiency greater than unity. These features are obtained in one construction with an electrode geometry which is similar to that of the double-surface transistor.[6] In the double-surface transistor the characteristics of the collector are modified by the injection of charge into the neighboring semiconductor from a nearby emitter electrode. In the present photo-cell the characteristics of the collector are modified by the photo-liberation of charge in the neighboring semiconductor. Figure 1 shows an illustrative drawing of such a photo-cell, in which the germanium has the dimpled pill-shape used in the Kock-Wallace transistor mounting.[7] The preparation of the (N-type) germanium wafer and the electrical forming treatment of the collector contact are described elsewhere.[8]

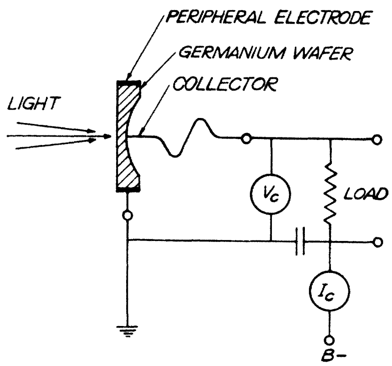

Fig. 1. Diagram of photo-cell showing electrical connections for testing and typical use.

The area of the germanium wafer over which incident light affects the cell resistance is confined to a region a few hundredths sq. mm in extent on the illuminated side immediately opposite the collector contact. The responsive areas of a number of cells have been explored with a small spot of light from the vertical illuminator attachment of a metallurgical microscope. When the resulting current response of a typical cell is plotted *vs.* distance along a line passing through the center of the responsive area, an error-function-shaped curve is obtained whose breadth at half-maximum, corrected for the diameter of the exploring light spit, is about 0.2 mm. Allowing light to fall uniformly all over the wafer surface not only wastes light, but avoids the realization of the spatial resolving power of which the cell is capable. In the measurement of the characteristics reported below a condensing lens was used to focus an image of the light source substantially within the responsive area of the cell under test.

In operation the collector is biased negatively with respect to the peripheral contact through a load resistance of from 5000 to 30,000 ohms. This polarity corresponds to the blocking direction of diode rectification of metal against N-type germanium at the collector contact. A family of static collector current *vs.* collector voltage curves for several different values of steady light flux is shown in Fig. 2. By selecting suitable battery voltage and load resistance values, drawing the corresponding load line across this family of characteristics, and analyzing, in the usual way, for the performance of the circuit, load power responses of the order of several tenths milliwatt per millilumen can be deduced. The response of the cell to different frequencies of modulation of the incident light is substantially flat to the highest frequency studied, about 200 kc per second.

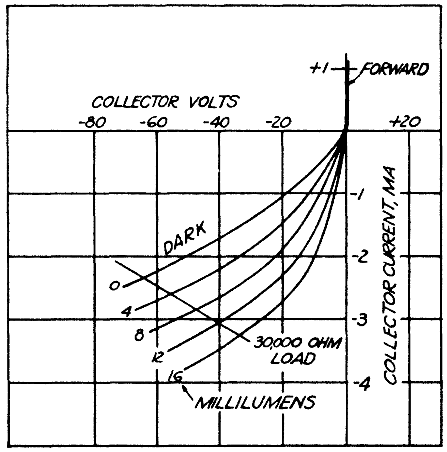

Fig. 2. Static characteristics of photo-cell.

Preliminary measurements of the spectral distribution of the sensitivity of the photo-cell have been made in collaboration with H. B. Briggs. The response rises slowly from visible yellow to a peak at about 1.5μ and decreases rapidly beyond 1.6μ. The shape of this response *vs.* wave-length relationship is practically identical with that determined by Goucher and Briggs for the photo-e.m.f. effect at N-P junctions in germanium. The breadth of the forbidden band in germanium, obtained from the intrinsic region of the resistivity-temperature relationship, corresponds to about 1.75μ. Detectable responses have been found for some germanium cells as far as 1.9μ.

Measurements of the over-all quantum efficiency of this cell show that with 1.5μ radiation, current increments corresponding to 3 or 4 electrons per incident quantum are realized. The seat of this effect is believed to be a current-multiplication occurring at the collector barrier in the process of collecting the primary charge already produced photoelectrically. The above current amplification is about the same as that ordinarily observed between emitter and collector in transistors.

[1] R. Bray and K. Lark-Horovitz, Phys. Rev. **71**, 141 (1947).
[2] S. Benzer, Phys. Rev. **72**, 1267 (1947).
[3] S. Benzer, Phys. Rev. **73**, 1256 (1948).
[4] S. Benzer, Phys. Rev. **69**, 683 (1946).
[5] F. S. Goucher, Phys. Rev. **75**, 1625 (1949).
[6] J. N. Shive, Phys. Rev. **75**, 689 (1949).
[7] W. E. Kock and K. L. Wallace, Jr., Elec. Eng. **68**, 222 (1949).
[8] J. Bardeen and W. H. Brattain, Phys. Rev. **74**, 230 (1948); also H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (McGraw-Hill Book Company, Inc., New York, 1948), Ch. X.

Neutron Induced Radioactivities in V^{52}, Mo^{99}, and W^{185}

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June 30, 1949

On exposing specimens of vanadium, molybdenum, and tungsten to neutron capture in the Argonne and Oak Ridge piles, certain new radioactivities are found to be produced. While our principal interest has been the spectrometric determination of gamma-rays by conversion electrons, observations are also made of the half-life and the energy of penetrating gamma-rays by absorption.

Vanadium. Since a single isotope of stable vanadium of mass 51 occurs in nature, the isotope formed by neutron capture should have the mass 52. The decay as observed showed clearly 2 half-lives; one of 16 hours and another of about 635 days. A half-life of 600 days had previously been reported for V47, which isotope could not possibly be produced here. Conversion electrons indicate the existence of gamma-rays of energy 80.5 and 119.3 kev for the long-lived emitter.

Molybdenum. A single radioactive isotope of molybdenum of probable mass 99, having a half-life of 68.3 hours, is produced. By absorptions in lead there appears to be a gamma-ray of energy about 0.78 Mev and conversion electrons indicate gamma-energies of 139.6, 167.6, and 179.3 kev.

Tungsten. The decay curve of tungsten is complex, showing a half-life of 25.0 hours (previously reported 24.1) and a long-lived emitter of half-life 76 days. Associated with the latter activity are two electron lines which, if interpreted as an *L–M* combination, yield a single gamma-ray at 133.7 kev.

This investigation is supported jointly by the ONR and the AEC.

Photo-Disintegration of Deuterium by Seven- to Twenty-Mev X-Rays*

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July 5, 1949

A PRELIMINARY study has been made of the angular distributions and distribution in energy of the protons arising from the photo-disintegration of deuterium by the continuous x-ray spectrum from 20.8 Mev electrons in the betatron. The x-rays were collimated into a beam having a full angular width of forty-six minutes by means of a laminated lead collimator placed between the coil boxes of the betatron. The collimated x-ray beam passed through a scattering chamber filled with deuterium gas. Ilford, type C-2, one hundred micron nuclear emulsions were placed inside the scattering chamber to one side of the x-ray beam to detect the protons resulting from the photo-disintegration of the deuterium gas in the beam. Plates were exposed with three atmospheres of deuterium to emphasize the high energy end of the spectrum, with one atmosphere of deuterium to emphasize the low energy end, and with one and three atmospheres of hydrogen. The exposures made with the chamber filled with hydrogen were used to determine the background due to the photo-neutrons coming from the lead collimator and shielding. At all energies this background was a small effect and at high energies it was completely negligible.

To date the analysis has been completed of about four square centimeters of the plates exposed with the chamber filled with three atmospheres of deuterium and the corresponding hydrogen background plates. The energy of each proton track as it entered the plate was determined from the range-energy relations for the Ilford emulsions.[1] These energies were then corrected for the range of each track in the gas of the chamber before it reached the emulsion. From the known geometry of the plates with respect to the x-ray beam and angular measurements made on each track it was possible to determine the angle each track made with respect to the direction of the incident quanta. Angles could be determined between 20 and 160 degrees in the laboratory system. The quantum energy corresponding to each track was calculated from the measured angle and energy of each track in the laboratory system.

Using the intensity spectrum of the betatron as determined by Koch and Carter,[2] Fig. 1 shows the relative cross section as a function of quantum energy for the photo-disintegration of deuterium as determined from these data. The scale on the left is in arbitrary units while that on right has been normalized such that the cross section at seven Mev is $11.7(10)^{-28}$ cm^2, the value given by the Bethe-Peierls expression. The dashed curve is the Bethe-Peierls expression for the cross section as a function of energy. The solid curve, which seems to fit the data at the high energy end, is for a cross section which varies as $1/(E)^{\frac{1}{2}}$, where E is the energy of the incident quantum. The various theoretical values calculated at 17.5 Mev by Rarita and Schwinger[3] have also been plotted.

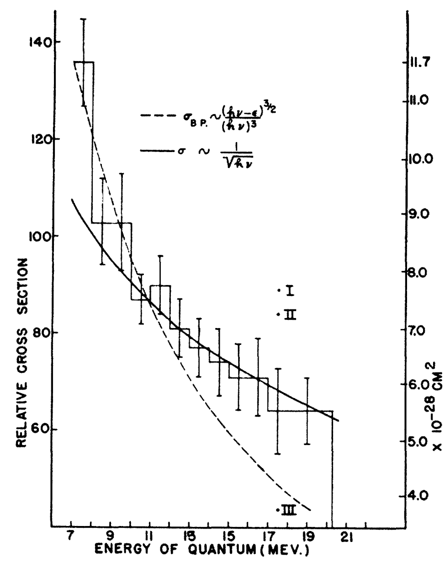

FIG. 1. Relative cross section for photo-disintegration of deuterium. Scale on right normalized to give cross section of $11.7(10)^{-28}$ cm^2 at 7 Mev. Points calculated by Rarita and Schwinger: *I* symmetrical theory, *II* charged theory, *III* neutral theory.

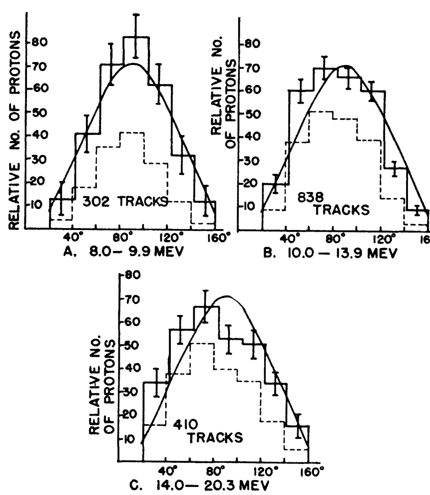

FIG. 2. Angular distributions of photo-protons. Dashed block diagrams: Relative numbers of tracks observed on plate in laboratory system. Solid block diagrams: Relative numbers of tracks per unit solid angle in center of mass system. Smooth curves: $\sin^2\theta$ distributions.

In Fig. 2 angular distributions have been plotted. In each case the dashed block diagram represents the observed distribution on the plate after correction for background. The solid block diagrams represent the distributions per unit solid angle normalized to the same area after conversion to the center of mass system. The smooth curve in each figure represents a $\sin^2\theta$ distribution. These data seem to indicate a possible forward asymmetry in the angular