A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power

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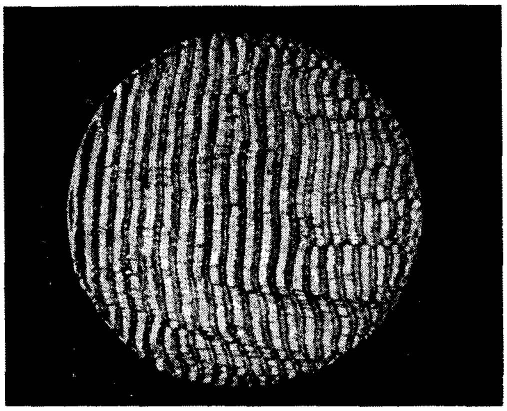

FIG. 1. End view of 0.50 caliber cylindrical steel projectile after it has passed through a 0.005-in. lead target at 45 deg striking angle. The actual diameter of this cylinder is 0.428 in.

Figure 1 is a photograph of the end of a 0.50 caliber cylindrical steel projectile after it has penetrated a 0.005-in. lead target aligned at a 45 deg striking angle. Figure 2 is a photomicrograph of a cross section of a cylinder that shows the wave structure of the ridges. Although the mechanism responsible for production of these waves is somewhat obscure, the critical angle 2φ is believed to be the same critical angle discussed by the Los Alamos group[1] in a paper that deals with metal plates accelerated together by high explosive charges. The Los Alamos group has discussed the asymmetric collision of dissimilar solids, but has not yet reported any experimental data. The specimens shown in Figs. 1 and 2 correspond to the asymmetric case.

The experiment was modified to obtain symmetric collision. Steel projectiles with conical noses specified by the half-angle $\pi/2-\theta$ were fired into steel targets aligned at the striking angle θ. Plastic deformation occurs along one of the elements of the cone provided that $2\theta>2\varphi$. Negligible plastic deformation occurs if $2\theta<2\varphi$. The critical angle 2φ determined by this experiment is in excellent agreement with the predicted[1] value for iron. Two preliminary determinations indicate the value $2\varphi=7.7$ deg for a projectile velocity of 0.87 mm/μsec. This velocity corresponds to the plate velocity $v_p=0.43$ mm/μsec of Fig. 15 in reference 1.

The experiment discussed is believed to be equivalent to that of the Los Alamos group. No theoretical or experimental difficulty is expected if the technique is extended to higher velocities and to solids other than steel. The experiment is expected to be of value in checking and determining equation of state data of solids in the megabar pressure regime. As a basis for comparison, the compressibility of pure iron has been measured up to a maximum pressure of only 0.03 megabar.[2] The pressure produced at the critical angle 2φ by the symmetric collision of steel is 0.47 megabar, a value calculated from the published[1] equation of state of iron.

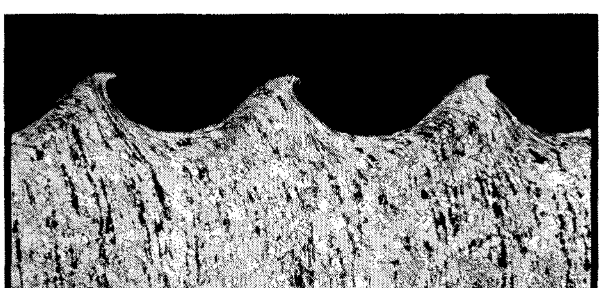

FIG. 2. Photomicrograph of a cross section of a projectile which shows the wave structure formed by 45 deg impact on a 0.010-in. lead target. The average distance from crest to crest is 0.033 in.

[1] Walsh, Shreffler, and Willig, J. Appl. Phys. 24, 349 (1953).
[2] P. W. Bridgman, Revs. Modern Phys. 18, 1 (1946).

A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

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THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

Photons of 1.02 electron volts ($\lambda=1.2$ microns) are able to produce electron-hole pairs in silicon. In the presence of a *p-n* barrier, these electron-hole pairs are separated and made to do work in an external circuit. All of the light of wavelength shorter than 1.2 microns is potentially useful for generating electron-hole pairs but the efficiency of energy conversion decreases for short wavelengths because the energy above the necessary 1.02 electron volts is wasted. Allowing for this loss and assuming a working voltage of 0.5 volt, which is near the maximum measured, a computation over the entire solar spectrum indicates a limiting efficiency of approximately 22 percent for a cell of negligible internal losses and for utilization of all possible electron-hole pairs.

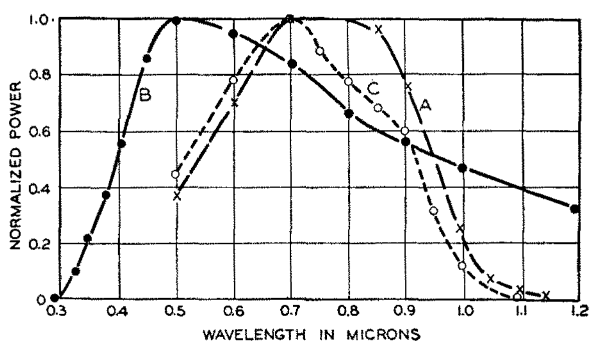

FIG. 1. Normalized spectral energy distribution. (A) Silicon photocell equi-energy response. (B) Solar energy at earth's surface. (C) Curve *A* times Curve *B*.

Several practical factors lower this figure. The untreated silicon surface reflects about half of the incident radiation. Some of this can be saved by proper surface treatment. The second serious loss is recombination of electron-hole pairs before they reach the *p-n* barrier. Penetration of radiation over most of the useful spectrum is extremely shallow so that it becomes necessary to place the *p-n* junction as near to the surface as possible except for the third serious loss. This is the I^2R loss caused by resistance in the surface layer and by contact resistance. Extremely small cells minimize the resistance loss and give useful data. For cells of several square centimeters, special geometry of contacts will minimize resistance losses.

Present work on silicon *p-n* photocells uses a thin layer of *p*-type silicon formed over an *n*-type base. The surface layer is less than 0.0001 inch thick. Figure 1 shows the spectral response for one such cell. Curve *A* is the measured power output for equal intensities of weak radiation as a function of wavelength. Maximum sensitivity is arbitrarily taken as unity. Ideally the maximum should appear near 1.2 microns with half this sensitivity at 0.6 and one-quarter at 0.3 micron. Curve B is the normal distribution of full sunlight[1] with the maximum expressed as unity. Curve C is the product of Curve A and Curve B again reduced to unity for maximum. This curve shows which part of the sun's radiation is most useful for this particular cell.

The photocells described here have been made to deliver power from the sun into a resistance load at the rate of 60 watts per square meter of photocell surface. This is approximately 6 percent efficiency and compares with a measured value of 0.5 percent on a commercially available photocell. The greatest over-all efficiency previously reported for direct conversion of solar radiation into electrical power is that of Telkes[2] using thermoelectric junctions and amounts to 1 percent.

We wish to thank H. B. Briggs who made the spectral measurements shown in Curve A.

[1] W. E. Forsythe, *Measurement of Radiant Energy* (McGraw-Hill Book Company, Inc., New York, 1937).
[2] Maria Telkes, J. Appl. Phys. **18**, 1116 (1947).

Dissected Amplifiers Using Negative Resistance

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(Received December 28, 1953)

It is the purpose of this communication to point out a line of attack upon the problem of making high-frequency semiconductor amplifiers. This attack may be described as the dissection of the amplification mechanism into its two constituents: negative resistance and directionality.

Negative resistance is a common feature of all amplifying devices operating from a dc power source. Thus the net ac power from the device when operating as an amplifier is positive. Since this power is the net flux of the ac part of Poynting's vector, it follows that Poynting's vector must have a positive divergence throughout certain "negative resistance regions." For a vacuum-tube triode amplifier, the grid-plate space is such a region, the current being high when the voltage is low and vice versa. Similarly, the space-charge region of the collector junction of a junction transistor amplifier has negative resistance. It should be noted that these negative resistances are not characteristic of the regions *per se* but instead of their behavior in an amplifier circuit.

This method of analysis enables one to evaluate quickly such proposals as the making of a junction transistor from isolated *p-n* junctions (impossible because no negative resistances can occur) or an amplifier from a nonlinear dielectric and dc power source.

Directionality arises in vacuum tubes and transistors because of the separation of input and output circuits. This leads to asymmetry in the current voltage matrix and permits the achievement of high gain by cascading stages without resultant instability.

Because the drift velocity of electrons (or holes) in semiconductors is smaller than the average transit velocity in vacuum tubes, the physical dimensions must be smaller for the same transit times. Although the solid nature of transistors gives them an inherent structural advantage over vacuum tubes, the smaller scale required for them poses serious problems of construction for devices in the highest-frequency ranges.

One way around this difficulty is to make two-terminal negative resistance devices in which only one dimension need be small. A variety of operating principles are possible for the operation of such devices.[1]

Two-terminal negative resistance devices have the disadvantage, however, that they do not have directionality; consequently, high gain is associated with narrow margins of stability.

This limitation may be overcome by adding directionality through passive elements[2] such as Hall effect couplers or gyrators[3] in wave guides.[4] Such combinations can simulate conventional amplifying devices such as a vacuum-tube triode. In Fig. 1 the hexagon represents a germanium plate with a magnetic field perpendicular to its plane. It contributes in Eqs. (1) and (2) the terms involving the conductance y_0 and the dimensionless quantity α which is an odd function of the Hall angle with $|\alpha|<1$:

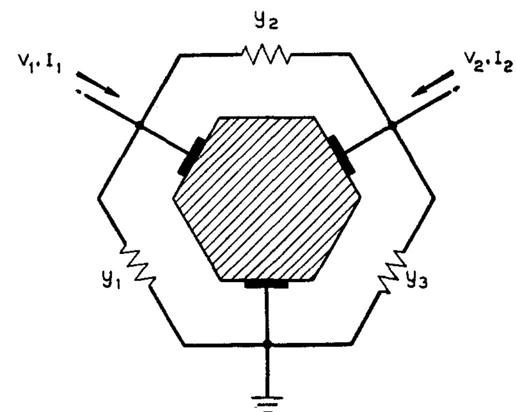

Fig. 1. Hall effect plate and three resistances. (Power supplies and connections necessary to power the negative resistances are not shown.)

$$I_1=(y_0+y_1+y_2)V_1-[\tfrac{1}{2}(1-\alpha)y_0+y_2]V_2, \tag{1}$$

$$I_2=-[\tfrac{1}{2}(1+\alpha)y_0+y_2]V_1+(y_0+y_2+y_3)V_2. \tag{2}$$

The conductances y_1, y_2, and y_3 may correspond to negative resistance elements. For example, if y_1, y_2, and y_3 have the values

$$y_1=y_3=-(1+\alpha)y_0/2, \tag{3}$$

$$y_2=(\alpha-1)y_0/2, \tag{4}$$

then Eqs. (1) and (2) reduce to

$$I_1=0 \text{ and } I_2=\alpha y_0 V_1. \tag{5}$$

This corresponds to an ideal pentode for $\alpha>0$ and to such a pentode with voltage reversing transformer for $\alpha<0$. Thus the circuit can simulate conventional amplifiers and in addition produce new types of devices.

Values of α as high as 0.2 can be obtained in n-type germanium at room temperature at fields of 17 500 oersteds. Similar reasoning to that discussed here applies also to the four-terminal Hall effect plate or balanced gyrator.[3]

A simple test[5] of this principle was made at low frequencies by putting two gas diodes with negative resistance characteristics on either side of the balanced gyrator of reference 3. With this arrangement a gain of 6 db was obtained in one direction, and a loss of 46 db in the other. By more careful balancing of the negative resistances with the input and output resistances of the gyrator, higher gains are possible without instability.

[1] A guide to one method of designing such semiconductor devices is furnished by the work of F. B. Llewellyn on transit time vacuum-tube diodes: Bell System Tech. J. **13**, 59–101 (1934); **15**, 575–586 (1936). Methods of extending this approach to semiconductors have been indicated by W. Schockley, U. S. Patent 2,623,102 (Junction Transistor). Another physical effect considered by one of us (W.S.) in unpublished work is the negative differential mobility to be expected for holes in very high electric fields. Interest in this predicted effect was the provoking cause of the research on high field mobilities, see E. J. Ryder and W. Shockley, Phys. Rev. **81**, 139 (1951) and E. J. Ryder, Phys. Rev. **90**, 766–769 (1953). The theory of this effect has been independently discovered by H. Krömer, Z. Physik **134**, 435 (1953), who calls it the "Staueffect" but does not consider its utilization as a power source.
[2] Passive elements can have the desired directionality, i.e., lead to unsymmetrical current-voltage matrices, only in the presence of magnetic fields. For a proof see H. B. G. Casimir, Revs. Modern Phys. **17**, 343–350 (1945).
[3] Mason, Hewitt, and Wick, J. Appl. Phys. **24**, 166–175 (1953). The fact that transmission through a crystal is nonreciprocal in the presence of a magnetic field was first pointed out by E. M. McMillan, J. Acoust. Soc. Am. **19**, 922 (1947).
[4] C. L. Hogan, Bell System Tech. J. **31**, 1–32 (1952).
[5] This test was made by W. H. Hewitt.