Letters to the Editor

Photovoltaic Effect in GaAs *p-n* Junctions and Solar Energy Conversion*

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THIS Letter describes some preliminary experiments on GaAs *p-n* junctions used as solar energy converters and compares their operation to that predicted by the theory of the photovoltaic effect. According to the theory of solar energy conversion by means of the photovoltaic effect, GaAs ($E_G = 1.35$ ev) is one of the materials which should potentially operate at a higher maximum efficiency, η_{max}, than Si, Se, CdS, or any of the other semiconductors which have been used
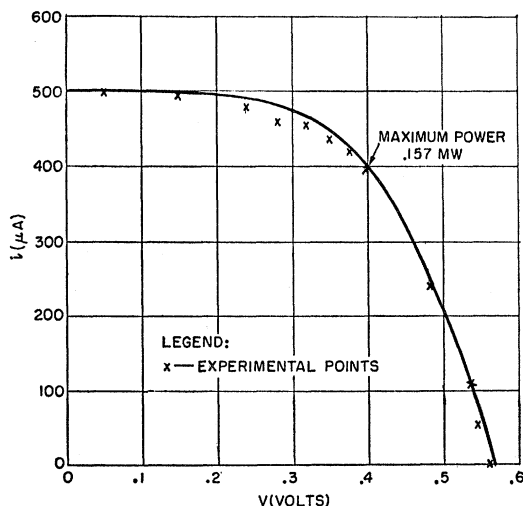

FIG. 1. Comparison of theoretical $i-V$ curve with experimental points obtained from solar illumination on a GaAs *p-n* junction.

for this purpose to date.[1] Since this work was completed, Gremmelmaier has reported similar observations.[2]

The *p-n* junctions were made by diffusing cadmium into an *n*-type single crystal wafer. Ohmic contacts were made to the resulting *p*-type surface and to the base. The junctions were exposed to sunlight and the voltage, V, which developed across a given load resistor, R_L, was plotted against the current i, through R_L as shown in Fig. 1. The maximum efficiency, η_{max}, was

determined from the ratio of the maximum power appearing across the load to the power received by the junction as measured by Eppley pyrheliometer.

Table I shows the results obtained on some GaAs *p-n* junctions made under varying conditions. The
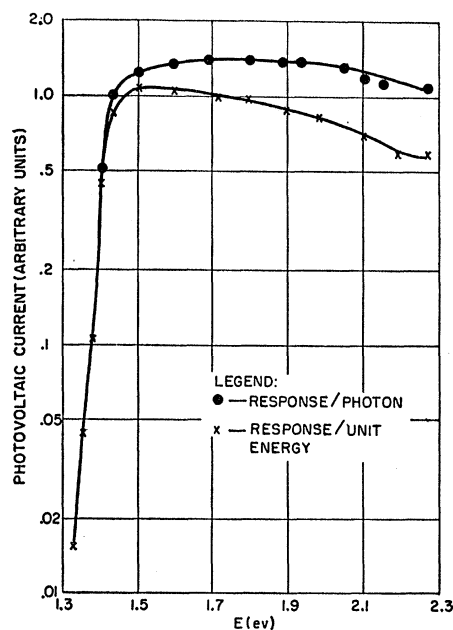

FIG. 2. Spectral response of GaAs photovoltaic *p-n* junction.

highest efficiency tabulated is 6.5%, which is the same order as published values for Si[3] and CdS.[4]

The experimental behavior of a typical GaAs cell is compared with theory in Fig. 1, which shows the current-voltage characteristic of unit No. 1. The solid curve was computed from the equation which governs the photovoltaic effect,

$$i = I_s - I_0(e^{\lambda V_j} - 1), \qquad (1)$$

where I_s is the measured short-circuit current caused by the proton excitation (5.0×10^{-4} amp), I_0 is the thermally induced reverse saturation current of the *p-n* junction, $\lambda = q/kT$, and V_j is the voltage across the junction given by

$$V_j = V + ir_s, \qquad (2)$$

where r_s is the internal series resistance. To obtain the best fit to the data, it was necessary to use these values of the parameters:

$$I_0 = 2.9 \times 10^{-8} \text{ amp}, \quad \lambda = 17, \quad r_s = 200 \text{ ohms}.$$

Thus I_0 is about 10^5 times greater than the value predicted for GaAs from the theory of *p-n* junctions. Furthermore, λ is less than 39.2 which is the expected value for $T = 300°K$. Such a disagreement with the theory of *p-n* junctions is not unique with GaAs; Kleinknecht has observed similar deviations in the rectifier characteristics of grown *p-n* junctions of silicon.[5]

The short-circuit current, I_s, should be proportional to the number of photons absorbed in the solid. The spectral response of the cells was therefore established by observing a quantity proportional to I_s as a function of photon energy. The results of such an experiment,[6] in which the photons were supplied by a monochromator, are shown in Fig. 2. The lower curve illustrates the

TABLE I. Efficiency of various GaAs solar generators.

Unit No.	Area 10^{-2} cm^2	Solar power input mw/cm^2	Max power output μw	η_{max} %
1	5.9	83	157	3.2
2	0.7	5.7	2.6	6.5
3	0.57	40	9.8	4.3
4	0.7	42.6	15.3	5.2
5	0.12	69	4.5	5.3
6	0.2	69	7.0	4.9

response per unit energy while the upper curve gives the response per photon. As expected, the latter is reasonably constant for a wide range of photon energies. Both curves indicate a cut-off energy of about 1.35 ev which corresponds to the energy gap of GaAs as determined from its optical transmission. The absolute quantum efficiency has not been measured, but it can be estimated from the ratio of I_s to the potential value of I_s if all those photons whose energy exceeds 1.35 ev were absorbed. This ratio is about 0.4. Some of the loss can be ascribed to reflection at the front surface, while another fraction is lost by recombination of the liberated carriers either at the exposed surface or in the bulk material.

The units described in this letter have not been designed to give optimum performance, so that it is reasonable to expect an increase in the efficiency of such cells as their technology improves.

[1] J. J. Loferski, presented at the Conference on Solar Energy, University of Arizona, October-November, 1955 (to be published).
[2] R. Gremmelmaier, Z. Naturforsch. 10a, 501 (1955).
[3] Chapin, Fuller, and Pearson, J. Appl. Phys. 25, 676 (1954).
[4] Reynolds, Leies, Antes, and Marburger, Phys. Rev. 96, 533 (1954).
[5] H. Kleinknecht and K. Seller, Z. Physik 139, 599 (1954).
[6] We are indebted to Dr. R. Braunstein of these Laboratories for aid in measuring the spectral response of the cells.

Self-Diffusion and Conductivity in Silver Chloride*

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TRANSPORT measurements by Tubandt[1] indicate that only the silver ions are mobile in silver chloride between 20°C and 350°C. The tracer diffusion coefficient, D_T, of the silver ion, as measured with the

Ag[110] isotope, does not agree, however, with the diffusion coefficient, D, calculated from the conductivity, σ, by the Einstein-Nernst[2] relation

$$D = (kT/Ne^2)\sigma \qquad (1)$$

where N is the number of silver ions per unit volume. The ratio, D/D_T, is 1.7.

Figure 1 shows diffusion data obtained from two portions of a silver chloride crystal.[3] The data on the upper curve represent the diffusion coefficients, D, as calculated from the measured ac conductivity by the use of Eq. (1). The data on the lower curve are the measured tracer diffusion coefficients, D_T. The measured intrinsic conductivities are in good agreement with those reported by Koch and Wagner[4] and Ebert and Teltow.[5]

The tracer diffusion coefficient of the chloride ion has been measured in AgCl by using the Cl[36] radioisotope. Between 443°C and 324°C the measured diffusion
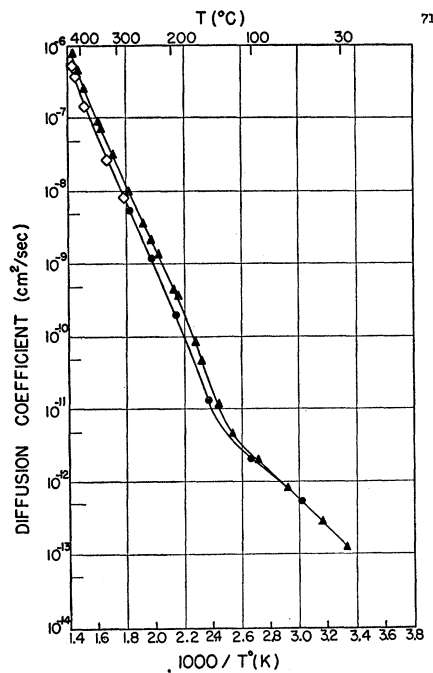

FIG. 1. Diffusion coefficients vs reciprocal absolute temperature in silver chloride. ▲—Diffusion coefficients calculated from the electrical conductivity by Eq. (1). ◊, ●—Diffusion coefficients of silver measured with Ag[110] radioisotope. Two different sections of the same crystal were used.

coefficient of the chloride ion is about 10^{-3} that of the silver ion. The failure of the Einstein-Nernst relation cannot be explained, therefore, as the result of a contribution, undetected by transport number measurements, of the chloride ion to the conductivity.

Figure 1 indicates that, at low temperature, the Einstein-Nernst relation is satisfied by the data. The ratio D/D_T, obtained from other silver chloride crystals, has been as large as 1.25 in the low-temperature region