

ponent of the earth's field is compensated. The resulting residual transverse magnetic field causes a spin precession after a first scattered photon which serves to destroy essentially all alignment and to restore thermal equilibrium before a second photon can be scattered. At values of the applied axial field far from 0.055 gauss, atoms are not restored to thermal equilibrium after scattering a photon and may scatter a second photon while in this non-equilibrium state. The polarization ratio of this second scattered photon is computed to be larger than that of the first photon scattered, in agreement with the experimental observations. The total observed shift in light polarization ratio should depend on the intensity of the light source, since this determines the number of atoms which scatter more than one photon. As expected, it is found experimentally that for the range of light intensity available, the shift in polarization ratio is in direct proportion to the intensity of the incident light. With the maximum intensity available, a shift of 0.0034 is calculated; the observed value is 0.0048, indicating that the incident light may not be completely unpolarized.

The alignment of sodium by the scattering of unpolarized light may be understood from reference 1, considering the unpolarized light as composed of equal numbers of right and left circularly polarized photons. In Table I of reference 1, it may be noted that the $m_F=0$ populations are reduced by the scattering of a circularly polarized photon independent of the rotational sense. Consequently, the scattering of an unpolarized photon will reduce the $m_F=0$ state populations relative to those with $|m_F|=F$, the condition of alignment. For two scattered photons there are atoms which scatter photons of the same polarization and contribute to the alignment of the ensemble and atoms which scatter oppositely polarized photons and do not contribute significantly. For more than two photons the process does not proceed to complete alignment but reaches an equilibrium partial alignment, for the effect of unpolarized resonance radiation on a completely aligned ensemble is to reduce the alignment.

TABLE I. Occupation numbers of atoms which have scattered n unpolarized photons, $n=\infty$ corresponding to the equilibrium state. P_1 and P_2 are the total numbers of atoms in the two hyperfine states. R_n is the polarization ratio of the n th scattered photon.

n	$F=1$			$F=2$		P_1	P_2	R_n
	± 1	0	± 2	± 1	0			
0	0.125	0.125	0.125	0.125	0.125	0.375	0.625	...
1	0.128	0.119	0.144	0.115	0.106	0.375	0.625	0.0700
2	0.128	0.116	0.154	0.110	0.100	0.372	0.628	0.0905
3	0.126	0.115	0.161	0.108	0.099	0.367	0.637	0.0997
∞	0.125	0.115	0.163	0.106	0.098	0.365	0.636	

Table I gives the probability of an atom being in various states having the quantum numbers F , m_F (total angular momentum, magnetic quantum number) after having scattered one, two, or three photons, as

well as the values at equilibrium. Although the approach to equilibrium is fairly rapid, the equilibrium alignment is seen to be small. The difference in populations of corresponding magnetic substates of the two hyperfine levels at equilibrium, although small, is many times that in thermal equilibrium at room temperature due to the energy separation.

There is no reason to believe that the effect should be confined to sodium, since the argument given for the production of alignment is quite general. It must be understood, however, that the argument applies only to light incident from a restricted part of a sphere; for isotropic unpolarized light defines no axis with respect to which alignment can take place.

I wish to thank Dr. R. H. Dicke for helpful discussion and criticism.

* Research supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

† National Science Foundation Predoctoral Fellow.

‡ Now at: Physikalisches Institut der E. T. H., Gloriastrasse 35, Zürich, Switzerland.

¹ W. B. Hawkins and R. H. Dicke, Phys. Rev. **91**, 1008 (1953).

Photovoltaic Effect in Cadmium Sulfide

D. C. REYNOLDS, G. LEIES, L. L. ANTES, AND R. E. MARBURGER
Aeronautical Research Laboratory, Wright Air Development Center,
Air Research and Development Command, United States Air Force,
Wright-Patterson Air Force Base, Ohio

(Received September 2, 1954)

DURING the course of a recent investigation with the photoconduction and rectification properties of CdS crystals, a pronounced photovoltaic effect was observed. The crystals used for this investigation were grown from the vapor phase by a technique previously reported.¹

The rectification studies were conducted on crystals using an indium base electrode and such metals as silver, copper, gold, and platinum as counter electrodes. It was in some of these rectifiers that pronounced photovoltaic effects were observed.

The photovoltaic cells that have been tested to date have been made by applying the base electrode and counter electrode on opposite faces of a CdS crystal approximately 3 mm thick. Light more or less parallel to the electrodes was then applied to the open face of the crystal. From this arrangement open-circuit voltages of 0.4 v have been measured in direct sunlight and 0.6 v in focused sunlight. Short-circuit currents of 15 ma cm⁻² have been measured in direct sunlight and 300 ma cm⁻² in focused sunlight. The photovoltaic effect has also been observed in pellets of CdS powder (pressed and fired); however, the current obtained from these cells is less than that obtained from a single crystal as expected. Work is currently being carried out to prepare a semitransparent electrode on one face so that crystals can be illuminated perpendicular to the face.

The spectral response of a typical cell is shown in Fig. 1. The peak in the red is interesting in that it is a region of considerable transparency.² This peak has been observed on all crystals with various types of electrodes. In some crystals the peak in the red is so pronounced it masks the peak in the green. This observed peak in the red may be explained on the basis of the conduction mechanism proposed by Brosser, Kallmann, and Warminsky.² It appears that by proper control of impurities the spectral response can be tailor-made within limits.

In measuring the spectral response it was observed that for some crystals the short-circuit current at a given wavelength grows or decays with time depending on the wavelength of the previous illumination. Under illumination of chopped white light (up to 18 000 interruptions per second), the voltage trace as observed

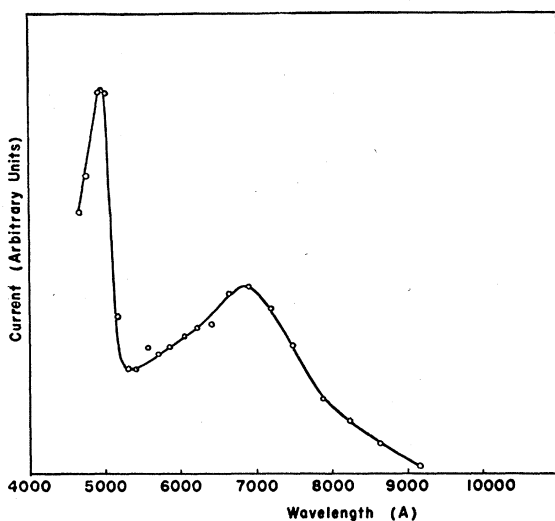


Fig. 1. Spectral photovoltaic response of CdS crystal with silver and indium electrodes.

on an oscilloscope retained the same shape although reduced in amplitude at the higher frequencies. This reduction may have been due to a capacitance effect.

With increasing intensity of illumination, the short-circuit current and the open-circuit voltage increased in such a manner as to give a linear increase of their product. Even up to intensities ten times that of sunlight, there appeared no indication of current or power saturation that could not be attributed to a temperature rise.

The average of all the crystals tested showed that the open-circuit voltage at room temperature dropped to half its value at approximately 150°C; and the closed-circuit current dropped to 80 percent of its room temperature value at approximately 150°C.

¹ Czyzak, Craig, McCain, and Reynolds, *J. Appl. Phys.* **23**, 932 (1952).

² Brosser, Kallmann, and Warminsky, *Z. Naturforsch.* **4a**, 631 (1949).

Optical and Infrared Absorption of Copper at 4.2°K

MANFRED A. BIONDI

Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania

(Received August 25, 1954)

RECENTLY, a number of theories have been published¹⁻³ concerning the anomalous skin effect in metals. These theories treat the case in which the electronic mean free path is large compared to the skin depth of penetration of an electromagnetic field, and hence the absorptivity of the metal is not properly described by conventional theory.⁴ Under these circumstances, the conduction electrons in the metal no longer make collisions in traversing the skin-depth region but collide only with the surface of the metal. The theories predict a different absorption of energy depending on whether the electrons are specularly or diffusely reflected from the surface of the metal. Holstein² has shown that in the high-frequency region (visible and infrared frequencies) if a fraction p of the electrons are specularly and $(1-p)$ are diffusely reflected from the surface, the absorptivity for normal incidence radiation is given by

$$A = A_{\text{spec}} + A_{\text{diff}} = p \frac{2\pi n e^2 v_0^3}{m^* \omega^2 c^3} + (1-p) \frac{3 v_0}{4 c}, \quad (1)$$

where v_0 is the Fermi velocity and m^* and n are the effective mass and density of the electrons, respectively. Ramanathan⁵ has measured the absorptivity of an electropolished copper surface at 4°K for room temperature radiation ($\lambda \sim 14 \mu$) and finds $A = 0.0062$, which is in order of magnitude agreement with the theory for $p=0$ (diffuse reflection).

In order to provide a more extensive test of the theory, an experiment was devised to measure the absorptivity as a function of the wavelength of the impinging radiation from $\lambda = 0.5 \mu$ to $\lambda = 4 \mu$. The principle of the measurements is illustrated in Fig. 1. Radiation of the desired wavelength is incident on a copper target which is mounted on a stage carrying a resistance thermometer and a heater winding. The stage is connected through a heat leak to the helium bath. The radiation reflected from the copper target is absorbed by the gold-black absorber stage,⁶ which also carries a resistance thermometer and a heater winding.

With the radiation turned on, the target and absorber stages reach an equilibrium temperature somewhat in excess of the bath temperature. The changes in resistance of the thermometers imbedded in the target and the absorber stages are noted. With the radiation off, power is applied to the heater in each stage to produce the resistance change noted with the radiation on. By measuring the heater power applied to each stage, one can determine the absorptivity of the copper target.