THE PHOTOMAGNETIC EFFECT IN ANOMALOUS-PHOTOVOLTAGE FILMS OF CADMIUM TELLURIDE

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Abstract

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1. When two adjacent p–n junctions are illuminated, the photovoltaic effects subtract, whereas the photomagnetic effects add. Yu. I. Ravich (^{1}), drawing attention to this circumstance, noted that in a system consisting of a large number of p–n junctions arranged in series, the photomagnetic effect (p.m.e.) can be considerably enhanced; this, in particular, makes promising the use of such a system as a highly sensitive magnetometer. According to Ravich' s theoretical estimates, the sensitivity of a p.m.e. sensor based on p–n junctions may attain the same order as the sensitivity of Hall sensors.

As far as we know, the p.m.e. in such a system of a large number of p–n junctions has not been studied, and a magnetometer of this type has not been realized experimentally. This is apparently due to considerable technological and design difficulties. Meanwhile, studies in the field of the effect of anomalously large photovoltages (the anomalous photovoltaic effect) have shown ($^{2-4}$) that, when prepared in a certain way, films of some semiconductors constitute a chain of tens and hundreds of thousands of microscopic p–n junctions. Such photovoltaic microbatteries, fabricated in a single technological process under a definite deposition regime, include, in particular, anomalous-photovoltaic films of cadmium telluride, which under illumination generate photovoltages V_{aph} of the order of hundreds and thousands of volts per centimeter of film length ($^{2-7}$).

For the reasons set forth above, the study of the p.m.e. in anomalous-photovoltaic films of cadmium telluride is, in our opinion, of interest for the theory of the p.m.e. in a p–n junction, for the theory of the complex of phenomena associated with the anomalous photovoltaic effect in semiconductor films, and also for clarifying the possibility of creating a miniature and highly sensitive film magnetometer.

2. The simplest model of an anomalous-photovoltaic film of cadmium telluride is shown in Fig. 1a. The absence of compensation of the photovoltages at the p–n and n–p junctions, leading to the appearance of

Fig. 1

Figure 1: Fig. 1

> $V_{\text{aph}} \sim 100 \div 1000$ V, is explained by the fact that the p-n and n-p junctions are located at different depths and therefore are illuminated differently. To compare the experimental results with the theory of the p.m.e. at p-n junctions, developed in ($^{1,8-10}$), we shall use a simplified, symmetric model shown in Fig. 1b, assuming that light falls on it through a grating that permits illumination of the p-n junctions and shades the n-p junctions. Although, within the limits of the linearity of the problem, compensation or decompensation of the microphotovoltages at the p-n junctions does not affect the magnitude of the total p.m.e., consideration of the model shown in Fig. 1b is fundamental both physically and methodologically.

We write the photomagnetic voltage in the open-circuit regime, $V_{\text{p.m.e.}}$, and the photomagnetic current under short-circuit conditions, $J_{\text{p.m.e.}}$, in the form (^{1})

$$V_{\text{p.m.e.}} = N\frac{kT}{q}\frac{(J_{p1}+J_{n1})H}{J_s+J_{p0}+J_{n0}}, \tag{1}$$

$$J_{\text{p.m.e.}} = (J_{p1}+J_{n1})H,$$

where N is the number of microphotoelements in the film; J_s is the dark saturation current at the p-n junction, and J_{p0}, J_{p1}, J_{n0}, and J_{n1} enter in the following way into the expressions for the hole and electron components of the photocurrent J_ϕ through the p-n junction:

$$|J_{\phi p}| = J_{p0}+J_{p1}I; \qquad |J_{\phi n}| = J_{n0}+J_{n1}H. \tag{2}$$

Here J_s, J_{p0}, etc. should be understood as the corresponding quantities averaged over all p-n junctions. Since for each p-n junction

Fig. 1. *a*—Tau ' s model of an AfN film of CdTl (^{14}); *b*—simplified model; *c*—model with a photoconducting shunt; *d*—equivalent circuit of the model with a shunt ($r_i = kT/q$, R_{sh} and R_{H} are, respectively, the differential resistances of the unbiased p-n junction, the shunt, and the load)

the transition current J_s depends neither on the light intensity I nor on the magnetic-field strength H, while J_{p0}, etc. are proportional to I and do not depend on H; obviously, the same remains true for the averaged quantities.

For $J_{p0}+J_{n0} \gg J_s$, the dependence $V_{\phi\text{.m.e.}}(I)$ becomes sublinear, and for $J_{p0}+J_{n0} \gg J_s$ it reaches saturation

Fig. 2

Figure 2: Fig. 2

Fig. 3 and Fig. 4

Figure 3: Fig. 3 and Fig. 4

$$V_{\phi.\text{m.e.}} = \frac{2}{\pi}\frac{kT}{q}N\mu\frac{H}{c}. \tag{3}$$

3. The method used by us to investigate the photomagnetic emf in AfN films is explained by the block diagram of the measuring setup shown in Fig. 2.

Fig. 2. Block diagram of the setup for measuring the photomagnetic emf in AfN films.
1—audio generator GZ-33; 2—power amplifier UM-50; 3—electromagnet in a resonant circuit, AfN film, and OI-24 illuminator; 4—cathode follower; 5—selective amplifier F-510; 6—VZ-13 voltmeter.

To separate the photomagnetic signal against the background of the considerably larger photovoltaic voltage of the AfN effect, the signals $V_{\phi.\text{m.e.}}$ and V_{afn} were separated in the frequency range. The films were illuminated with light of constant intensity I ($0 \div 170 \cdot 10^{-3}$ lx), and a sinusoidal magnetic field (20 Hz; $0 \div 130$ Oe) was produced by an electromagnet included in a resonant LC circuit. To narrow the noise bandwidth and to filter out the background signal arising from the illuminator, a selective amplifier was used. Specific difficulties caused by the high resistance of AfN—

films ($\sim 10^{10} \div 10^{13}$ Ω), were eliminated by introducing into the circuit a cathode follower with an input impedance of $5 \cdot 10^{10}$ Ω.

The described technique is analogous to the method of measuring the Hall effect with direct current in an alternating magnetic field. According to the data of work (^{11}),

Fig. 3. Dependence of the open-circuit photomagnetic voltage on light intensity:
1 –22 Oe; 2 –43 Oe; 3 –65 Oe; 4 –87 Oe; 5 –108 Oe; 6 –130 Oe. Curve 7 – $V_{\text{afn}}(I)$.

Fig. 4. Dependence of the open-circuit photomagnetic voltage on magnetic-field strength.
1 $-\gtrsim$ 80 000 lx (5.4 mV/Oe); 2 –17,000 lx (3.6 mV/Oe); 3 –6000 lx ($\partial V_{\text{ph.m.e.}}/\partial H = 1.92$ mV/Oe).

its sensitivity is 10^{-8} V at a sample resistance of $\sim 10^{9}$ Ω.

4. Typical experimental curves $V_{\text{ph.m.e.}}(I)$ and $V_{\text{ph.m.e.}}(H)$ in CdTe films are shown in Figs. 3 and 4. The experimentally established linearity of $V_{\text{ph.m.e.}}(H)$, as well as the form of the curves $V_{\text{ph.m.e.}}(I)$ (sublinearity and saturation), correspond to the theoretical formulas (1)-(3).

The characteristics of the 6 investigated afn CdTe films are given in Table 1 ($I = 168 \cdot 10^3$ lx; $H = 130$ Oe). The values of the effective carrier mobility μ were calculated from formula (3) under the assumption that the number of micro-p—n junctions in the film is $N = 10^5$.

Table 1

Sample Nos.	V_{afn}, V	$V_{\text{ph.m.e.}}$, V	R, Ω (under illumination)	Sensitivity, mV/Oe	μ, cm^2/(V • s)
1	220	0.6	$2 \cdot 10^{10}$	4.7	150
2	320	0.35	$2 \cdot 10^{10}$	2.7	87
3	20	0.68	$1.5 \cdot 10^{10}$	5.4	168
4	120	0.33	$1 \cdot 10^{10}$	2.6	83
5	120	0.36	$2 \cdot 10^{9}$	2.8	90
6	350	0.4	$1 \cdot 10^{10}$	3.2	100

According to theory, saturation of $V_{\text{ph.m.e.}}$ should occur when $J_\phi \gg J_s$, i.e., under such conditions that

$$V_{\text{afn}} = N\frac{kT}{q}\ln\left(1+\frac{J_\phi}{J_s}\right) \tag{4}$$

leads to a logarithmic dependence on the light intensity I (photocurrent $J_\phi = aI$). The lux-volt characteristic of the afn-

of the effect shows that this is in fact what occurs. However, according to (4), the numerical values of V_{afn} in this region should be $\sim NkT/q \sim 10\,000$ V, whereas experiment gives values of $\sim 100 \div 500$ V. The assumption that $N \neq 10^5$, but is smaller by 1.5-2 orders of magnitude, leads to very large values of μ (see Table 1). Apparently, these quantitative discrepancies are due to an excessive simplification of the models shown in Figs. 1*a* and *b*. In (^{12,13}) it was shown that the p-n junctions in afn films of cadmium telluride are located in a comparatively thin near-surface layer, while the remaining volume of the film is a photovoltage-inactive photoconducting shunt. Analysis of such a model (Fig. 1*v*), whose equivalent circuit is given in Fig. 1*g*, gives the following expression for V_{afn} under open-circuit conditions:

$$V_{\text{afn}} = \frac{Nr_{iJ_\phi}}{1+Nr_i/R_{\text{sh}}}. \tag{5}$$

Putting $1/R_{\text{sh}} = 1/R_0 + \gamma I$, we find that for $I \gg 1/\gamma R_0$ and $I \gg 1/\gamma N r_i$ the photovoltages developed in afn films of cadmium telluride reach values of the order of

$$V_{\text{afn}} \approx J_\phi R_{\text{sh}} \approx a/\gamma. \tag{6}$$

The values of a and γ, found from the experimental lux-ampere and lux-ohmic characteristics of CdTe films (^{12}), are $a \sim 10^{-12}$ A/lux; $\gamma \sim 10^{-14}\,1/(\Omega \cdot \text{lux})$. Accordingly, we obtain $V_{\text{afn}} \sim 100$ V, which agrees with experiment.

The model shown in Fig. 1*v* made it possible to explain a number of experimental facts (^{12,13}) that are inexplicable within the framework of Tauc' s model (Fig. 1*a*). We see that it also eliminates the quantitative discrepancy between the theoretical and experimental values of V_{afn}.

5. The data presented in Table 1 and in Figs. 3 and 4 show that the photomagnetic voltage in afn films of cadmium telluride amounts to several tenths of a volt. It is significant that such large $V_{\text{ph.m.e.}}$ values are developed at comparatively low magnetic-field strengths (100 oersted). Consequently, afn CdTe films can serve as highly sensitive miniature magnetic-field-strength sensors; moreover, the experimentally achieved sensitivity ($\approx 2 \div 5$ mV/oersted) already exceeds the sensitivity of Hall sensors.

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