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Abstract

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PHYSICS

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ON THE BARRIER AND DIFFUSION PHOTO-E.M.F.

1. When, under the influence of some external actions, a current arises in a circuit and power is released, the active element is characterized by an electromotive force, which is calculated theoretically and determined experimentally as the open-circuit voltage. Meanwhile, neither the very existence of an e.m.f. nor its equality to the open-circuit voltage follows at all from the fact that a current is generated in a closed circuit. Such an introduction of e.m.f. is the result of an uncritical application of Maxwell' s equation

$$\mathbf{i} = \sigma\left(\mathbf{E} + \mathbf{E}^{\text{str}}\right) \tag{1}$$

in its usual interpretation as an explicit expression of the functional dependence of the current density.

We shall denote, in the form of the argument I, that physical action which is the primary cause of the current J in the circuit (light intensity, temperature gradient, etc.). Only in the case when $\mathbf{E}^{\text{str}} = \mathbf{E}^{\text{str}}(\mathbf{r}, I)$ does the generator possess a definite e.m.f.

$$\mathcal{E}(I) = \oint \mathbf{E}^{\text{str}}(\mathbf{r}, I)\, d\mathbf{r}. \tag{2}$$

In the more general a priori possible case, when $\mathbf{E}^{\text{str}} = \mathbf{E}^{\text{str}}(\mathbf{r}, I, J)$, the circulation of the external forces

$$\oint \mathbf{E}^{\text{str}}\, d\mathbf{r} = \mathcal{E}(I, J) \tag{3}$$

is a function of two, within certain limits independent, arguments I and J (J, for a given I, can be varied by changing the load resistance in the circuit). Since

Fig. 1

Figure 1: Fig. 1

$\oint \mathbf{E}^{\text{str}}\, d\mathbf{r}$ depends on the magnitude of the current in the circuit, the generator cannot be characterized by a definite e.m.f.

2. From the integral of expression (1),

$$\mathcal{E}(I, J) = JR + JR' \tag{4}$$

it follows that an electric circuit containing a generator that does not possess an e.m.f., as a rule, must be nonlinear. The dependence of $\mathcal{E}$ on J introduces an additional and physically distinct factor of nonlinearity, alongside the possible dependence of the internal resistance of the generator R' on I (and also, possibly, on J). Only in the region of small currents, when the problem is linearized, can such a generator be characterized by an e.m.f. by means of an additive change of its internal resistance.

3. The considerations set forth above apply directly to semiconductor generators, which is completely disregarded in the modern specialized and general literature ([1–6]). Comparison of (1) with the expression for the current density ([4])

$$\mathbf{i} = \sigma \left[\mathbf{E} + \frac{\sigma_n \operatorname{grad} \zeta_n - \sigma_p \operatorname{grad} \zeta_p}{e\sigma} + \frac{\sigma_n S_n^* - \sigma_p S_p^*}{e\sigma} \operatorname{grad} T \right] \tag{5}$$

shows that

$$\mathbf{E}^{\text{str}} = \frac{\sigma_n \operatorname{grad} \zeta_n - \sigma_p \operatorname{grad} \zeta_p}{e\sigma} + \frac{\sigma_n S_n^* - \sigma_p S_p^*}{e\sigma} \operatorname{grad} T. \tag{6}$$

To calculate the intensity $\mathbf{E}^{\text{str}}$ and the circulation $\mathcal{E} = \oint \mathbf{E}^{\text{str}}\, d\mathbf{r}$ of the extraneous forces, it is necessary to solve the system of kinetic equations. Both the equations and the boundary conditions contain J, as a result of which $\mathcal{E} = \mathcal{E}(I, J)$. Since throughout the calculation it is assumed that the e.m.f. is equal to the open-circuit voltage ($J = 0$), the dependence of the circulation of extraneous forces in the semiconductor on the current strength proves to be lost. As a result, a quite definite electromotive force $\mathcal{E}_0 = V_{\text{xx}}$ is incorrectly ascribed to a semiconductor generator, while effects caused by the dependence of $\mathcal{E}$ on J are erroneously interpreted as a nonlinearity of the internal resistance.

Fig. 1

4. An example of a generator that has no e.m.f. may be a barrier-layer photocell. Its physical characteristic is the photocurrent, or collection current, J_0, equal to the sum of the currents passing through the p–n junction,

produced by holes generated by light in the n-region and by electrons generated by light in the p-region. Therefore representing a barrier-layer photocell in an equivalent circuit as a current generator shunted by the nonlinear internal resistance of the p–n junction (Fig. 1a) makes it possible to obtain directly the current-voltage and lux-ampere characteristics of the circuit ([1,7]). Of course, the same circuit can be modeled by an equivalent circuit with the photocell represented as a voltage generator (Fig. 1b). However, the e.m.f. of such a generator is equal to

$$\mathcal{E} = \frac{kT}{q} \ln \left(1 + \frac{J_0 - J}{J_s} \right), \tag{7}$$

i.e., it depends on the current in the circuit. It should be emphasized that it is precisely the e.m.f. of the equivalent voltage generator modeling the barrier-layer photocell, and not only the terminal voltage, that depends on the magnitude of the current. Indeed, if to the equivalent voltage generator one ascribes an e.m.f. equal to the open-circuit voltage of the element,

$$\mathcal{E}_0 = \frac{kT}{q} \ln \left(1 + \frac{J_0}{J_s} \right), \tag{8}$$

then, in order to obtain the correct value of the terminal voltage, it is necessary to introduce into the equivalent circuit, in series with the load, a nonlinear resistance

$$R' = \frac{kT}{qJ} \ln \left(1 + \frac{J}{J_0 + J_s - J} \right),$$

which has a fictitious character and does not reflect the current-voltage relations in the p–n junction. This also means that light does not create a definite e.m.f. in a barrier-layer photocell.

In the region of small currents ($J \ll J_s$), the introduction of the differential resistance of the p–n junction $R' = kT/qJ_s$ as a shunt to the current generator J_0 (Fig. 1a) and as an additional load to the voltage generator $\mathcal{E}_0 = V_{\text{xx}} = \frac{kT}{qJ_s} J_0$ (Fig. 1b) leads to identical results:

$$\text{a) } J_0 = J + J' = J \left(1 + \frac{qJ_{sR}}{kT} \right); \qquad \text{b) } \mathcal{E}_0 = \frac{kT}{qJ_s} J_0 = \frac{kT}{qJ_s} J + RJ, \tag{9}$$

as follows also from general considerations.

5. For Dember (diffusion) photocells

$$\mathcal{E} = \frac{kT}{q}\frac{b-1}{b+1}\ln\frac{1+\dfrac{b+1}{p_0+bn_0}p_0'}{1+\dfrac{b+1}{p_0+bn_0}p_l'}, \tag{10}$$

where (8)

$$p' = B_3e^{-\lambda x} + A_3e^{\gamma_1 x} + A_4e^{\gamma_2 x}, \tag{11}$$

$$i_p = q\mu p_0\widetilde{E} + B_4e^{-\lambda x} - \frac{q}{\tau^*\gamma_1}A_3e^{\gamma_1 x} - \frac{q}{\tau^*\gamma_2}A_4e^{\gamma_2 x},$$

and the field strength in the quasineutral region of the semiconductor $\widetilde{E}$ is a quasiconstant, varying from the value B_1 at $x \to 0$ to B_2 at $x \to l$, where

$$B_1 = -\frac{(b-1)i_{p0}+i}{qb\mu\,(p_0+n_0+2p_0')},$$

$$B_2 = -\frac{(b-1)i_{pl}+i}{qb\mu\,(p_0+n_0+2p_l')}. \tag{12}$$

Here $\gamma_1, \gamma_2, B_3, B_4, A_3, A_4$ are represented by the same expressions as in (8), but depend on the current, since these expressions contain $\widetilde{E}(J)$. Consequently, in the Dember effect as well, no definite photo-emf arises that is uniquely determined by the characteristics of the semiconductor and by the spectral composition and intensity of the light.

Analysis of the expressions written above shows that the current dependence of $\mathcal{E}$ for the Dember effect is weaker than the current dependence of $\mathcal{E}$ for a barrier-layer photocell. A circuit with a Dember photocell remains linear as long as the condition of a low generation level, $\Delta\sigma \ll \sigma_0$, is satisfied, whereas a circuit with a barrier-layer photocell is linearized only when the inequality $J \ll J_s$ is fulfilled, which is violated much earlier than the inequality $\Delta\sigma \ll \sigma_0$. This circumstance can be used for the experimental separation and study of the Dember photoeffect against the background of barrier-layer photovoltages arising because of non-ohmic contacts.

From (12) it follows that

$$i \approx (b-1)qD\frac{dp_0'}{dx} + \sigma_0\widetilde{E}_0 \approx (b-1)qD\frac{dp_l'}{dx} + \sigma_l\widetilde{E}_l. \tag{13}$$

The region where the diffusion currents are small constitutes the ballast internal resistance of the Dember photocell, preventing the attainment of an undistorted short-circuit current. If this internal resistance is small, then the lux-ampere characteristic of the photodiffusion short-circuit current is determined from the condition $B_1 = 0$ and, accordingly, for the normal and anomalous Dember effect (8) has the following form:

$$i = -qD(b-1)\frac{G_0}{\varkappa_1 L + D}, \qquad i = q(b-1)\lambda_1 IL. \tag{14}$$

A more detailed calculation of Dember lux-ampere, lux-volt, and volt-ampere characteristics will be carried out separately.

6. The existence of a definite emf in chemical cells is due, as is known, to the fact that the passage of a unit charge in a circuit with such a source is accompanied by the release of a quite definite amount of free energy of chemical transformation, independently of

current strength. In metals, because of the smallness of the Debye length, the contact potential difference is superposed on the surface barriers of the electron affinity. As a result, the circulation of extraneous forces is composed of the sum of surface jumps that depend on the temperature of the contacts but are not controlled by the current. By contrast, in semiconductors (metal–semiconductor contact; p–n junction) the change in electron affinity and the contact potential difference are spatially separated. The former is localized at the interface (for an external contact), the latter in the bulk. Owing to the finite extent and finite (in p–n junctions and blocking layers, increased) resistance of the space-charge region, a change in the side mode of the circuit is accompanied by a change in the height of the barrier that determines the contribution of the given contact or p–n junction to the circulation of extraneous forces. Therefore $\mathcal{E} = \oint \mathbf{E}^{\mathrm{str}}\, dr$ depends on the magnitude of the current in the circuit, i.e., semiconductor generators cannot be characterized by a definite electromotive force depending only on the nature and magnitude of the nonequilibrium action.

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Note: Figure translations are in progress. See original paper for figures.