

## Theory of Thermoelectric Power in Semiconductors

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An error occurring in a paper by Johnson and Lark-Horowitz is corrected by calculating the thermoelectric power directly from the electrical current density expression. A general equation for the thermoelectric power is given which holds for semiconductors with one or two kinds of current carriers in thermal equilibrium governed by classical or Fermi-Dirac statistics.

THE thermoelectric power  $Q$  of a semiconductor is determined by Johnson and Lark-Horowitz,<sup>1</sup> by calculating the Thomson coefficient and then integrating the Thomson relation. However, it is possible to obtain an expression for  $Q$  directly from Eq. (I-6),<sup>2</sup> the equation for the electric current density. It can be shown that this procedure yields in general an expression for  $Q$  which differs slightly from that given by Johnson and Lark-Horowitz and which seems to be more correct. For the sake of simplicity we shall discuss here explicitly the case of a semiconductor in the intrinsic range when the assumptions (A), (B), (C) in part III of reference 1 are valid. Putting  $j_x=0$  into Eq. (I-6), we obtain after a simple rearrangement

$$E_x = -\frac{1}{e} \left\{ \frac{cn_1}{cn_1+n_2} \left[ T \frac{d}{dx} \left( \frac{\xi}{T} \right) + \frac{1}{T} \frac{L_2(1)}{L_1(1)} \frac{dT}{dx} \right] - \frac{n_2}{cn_1+n_2} \left[ -T \frac{d}{dx} \left( \frac{E_G+\xi}{T} \right) + \frac{1}{T} \frac{L_2(2)}{L_1(2)} \frac{dT}{dx} \right] \right\}. \quad (1)$$

The thermoelectric power  $Q$  can be determined from the relation,

$$Q = -\frac{d}{dT} \oint E_x dx. \quad (2)$$

The integration on the right side of Eq. (2) is easily carried out in the intrinsic range when  $n_1=n_2$ . Integrating by parts, one obtains

$$\oint T \frac{d}{dx} \left( \frac{\xi}{T} \right) dx = - \oint \frac{\xi}{T} dT, \\ \oint T \frac{d}{dx} \left( \frac{E_G+\xi}{T} \right) dx = - \oint \frac{E_G+\xi}{T} dT,$$

as the integration in Eq. (2) must be performed over the

<sup>1</sup> V. A. Johnson and K. Lark-Horowitz, Phys. Rev. **92**, 226 (1953).

<sup>2</sup> Equation numbers like (I-6) refer to the equations in reference 1. The symbols used in the present note are the same as in reference 1.

whole circuit whose two ends are in the same state. Assuming the validity of Eq. (I-28), we thus obtain for  $Q$  the following expression:

$$Q = - \left[ \frac{k}{e} \frac{c-1}{c+1} \left( \frac{E_G}{2kT} + 2 \right) + \frac{3}{4} \ln \frac{m_1}{m_2} \right], \quad (3)$$

differing from Eq. (I-19) by a constant,  $-\frac{3}{4}(k/e) \times \ln(m_1/m_2)$ . This can be simply explained in the following way. By integration of Eq. (I-18) Johnson and Lark-Horowitz obtain in reality the expression (I-19) plus some constant which they put arbitrarily equal to zero. In our opinion, the correct value for this constant is found by our procedure.

Putting  $m_2/m_1=1.6$  into Eq. (3), one obtains for a value of about  $-3.41 \times 10^{-4}$  ev/°K instead of the values given in Table I of reference 1.

It is easy to calculate  $Q$  by the given procedure in the general case, as has been done previously.<sup>3</sup> It can be shown that Eq. (I-24) is valid exactly and not only approximately as stated by Johnson and Lark-Horowitz. It is perhaps interesting to remark that the expression for  $Q$  can be put into a general form with a simple physical interpretation (see reference 3):

$$Q = \frac{cn_1}{cn_1+n_2} Q_1 + \frac{n_2}{cn_1+n_2} Q_2. \quad (4)$$

$$Q_1 = \frac{k}{e} \frac{\xi - L_2(1)/L_1(1)}{kT}, \\ Q_2 = -\frac{k}{e} \frac{\xi + E_G + L_2(2)/L_1(2)}{kT}.$$

Equation (4) holds for thermal equilibrium governed by classical or Fermi-Dirac statistics. It reduces to Eqs. (3), (I-24), (I-26a), or (I-26b) under special assumptions. For  $n_2=0$  and a highly degenerate electron gas it gives the well-known expression for the thermoelectric power of metals.

<sup>3</sup> J. Tauc, Czechoslov. J. Phys. **3**, 282 (1953).