In conclusion it should be noted that one of the basic advantages of the proposed method is that it ensures agreement of λ with the thermal data p, v, T.

NOTATION

p	is the pressure;
v	is the specific volume;
T	is the temperature;
R	is the universal gas constant;
ρ	is the density;
ρ_s	is the density of saturated liquid;
B, H, and B_λ, H_λ	are the coefficients of Eqs. (1), (2), temperature-dependent;
λ	is the thermal-conductivity coefficient;
λ'_s	is the thermal-conductivity coefficient of saturated liquid.

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CALCULATING SEMICONDUCTOR PARAMETERS BASED ON MEASURING ELECTRICAL AND THERMOPHYSICAL, GALVANIC AND THERMOMAGNETIC EFFECTS USING THE METHOD OF VARYING THE INFLUENCE FACTORS

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The methods and the sequence for calculating the semiconductor parameters using the results of measuring the effects of a single experiment are examined. Algorithms for calculating the primary and secondary semiconductor parameters are proposed.

Lisker [1] proposed experimental investigation methods based on the principle formulated by the author of varying the influence factors in an experiment and demonstrated the feasibility of separate determination in a single experiment of all of the electrical and thermophysical, galvanic and thermomagnetic effects (GTME) in solids, arising under the influence of thermal, electric, and magnetic fields.

The most important consequence of the method of varying the influence factors is the possibility of obtaining the maximum amount of physical data during the course of a single experiment under a given number of

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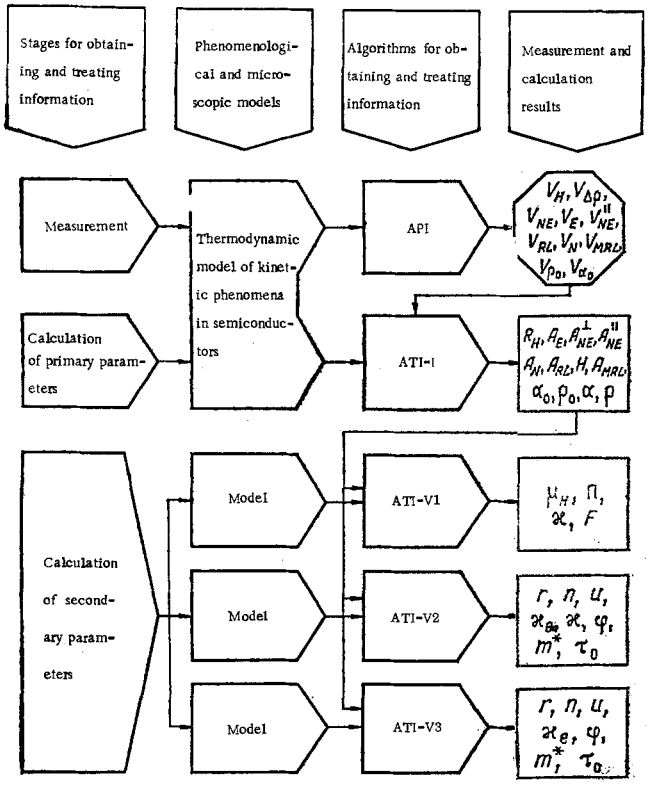

Fig. 1. Structure and organization of process for obtaining and treating information in an experiment.

force fields. Lisker and Pevzner [2] established that taking into consideration the identical relationships between the corresponding primary and the imposed thermomagnetic effects, the same result can be obtained by varying only two fields, the electric and the magnetic, at the fixed value of the third, the thermal gradient field in the specimen. The latter circumstance made it possible to considerably simplify carrying out the experiment and to present it in the formalized form of algorithms of physical investigation (API). Separate determination of all GTME gives the investigator additional primary information which is usually irretrievably lost when using former methods [3].

In connection with this, it is necessary to rationally organize the process of treating the large amount of primary information obtained while carrying out the experiment, and to work out suitable programs for calculating the primary and the secondary parameters. Here the primary information is understood to be the electrical signals which characterize the reaction of the examined object to the given influence factors and the extent (magnitude and direction) of the latter; the primary parameters characterize the connection between the force fields and the currents, while the secondary parameters characterize the examined models of the solid.

This article is devoted to laying foundations for the methods and the sequence of calculating the investigated parameters, to the formal description of this process, and also to the examination of the proposed algorithms for the treatment of information (ATI) specifically for the investigation of GTME. Moreover, only those experiments are examined in which the primary information is recorded after the completion of the process of establishing the thermodynamically stable state in the investigated object, caused by the action of a given group of factors. The additional information on parameters, which can be obtained from the temperature and field dependences of the experimental values, was not examined in this article. Let us emphasize that in order to preserve the maximum authenticity of the calculation results, only the values obtained in the present experiment are used in the examined algorithms.

The performance of any complete (i.e., such in which the operations of obtaining and treating the data are realized in a programmed and automated manner in a single experiment) physical experiment can be divided into three stages (see diagram).

TABLE 1. Algorithm for Calculating Primary ATI-I Parameters

Calculation step	Primary parameter	Formula for calculation	Parameters used	Literature cited
1.1	Hall coefficient	V_H/jBd		[4]
1.2	Nernst-Ettingshausen cross section $A_{NE}^{\perp}$	$V_{NE}^{\perp}/\nabla TBd$		[4]
1.3	Specific resistance	V_{ρ_0}/jl		[4]
1.4	Specific resistance	$(V_{\rho_0}+V_{\Delta\rho})/jl$		
1.5	Thermal emf ($B = 0$) α_0	$V_{\alpha_0}/\nabla Tl$		[4]
1.6	Thermal emf ($B \neq 0$) α	$(V_{\alpha_0}+V_{NE}'')/\nabla Tl$		
1.7	Ettingshausen A_E	$V_E/\alpha jBd$	α from (1.6)	[4]
1.8	Righi-Leduc A_{RL}	$V_{RL}/\alpha\nabla TBd$	α from (1.6)	[4]
1.9	Nernst A_N	$V_N/\alpha jB^2l$	α from (1.6)	[4]
1.10	Maggi-Righi-Leduc A_{MRL}	$-V_{MRL}/\alpha\nabla TB^2l$	α from (1.6)	[4]
1.11	Gauss coefficient (magnetic resistance) H	$V_{\Delta\rho}/V_{\rho_0}B^2$		
1.12	Nernst-Ettingshausen Longitudinal $A_{NE}^{\parallel}$	$V_{NE}''/V_{\alpha_0}B^2$		

TABLE 2. Algorithm for Calculating Secondary ATI-V1 Parameters (magnetic field of arbitrary intensity)

Calculation step	Parameter	Formula for calculation	Primary parameters used	Literature cited
2.1	Hall mobility μ_H	$\frac{R_H}{\rho}$	R_H from (1.1) ρ from (1.4)	[4]
2.2	Fermi level F	$eT\left(A_{NE}^{\perp}\frac{A_N}{A_E}B^2-\alpha\right)$	$A_{NE}^{\perp}$ from (1.2) α from (1.6) A_E from (1.7) A_N from (1.9)	
2.3	Peltier coefficient Π	$A_{NE}^{\perp}\left(\frac{A_N}{A_E}-\mu_H\right)TB^2$	$A_{NE}^{\perp}$ from (1.2) A_E from (1.7) A_N from (1.9) μ_H from (2.1)	
2.4	Complete thermal-conductivity coefficient $\varkappa$	$A_{NE}^{\perp}\left(\frac{1}{A_E}-\frac{A_{NE}^{\perp}}{\rho}B^2\right)T$	$A_{NE}^{\perp}$ from (1.2) A_E from (1.7) ρ from (1.4)	

In the first stage, which refers to the experimental part of the investigation [2], the primary signals of information V_i, which characterize all effects originating during a given variation of the influence factors, are measured at various points in time.

In the second stage, the primary parameters A_i, which correspond to the basic and the imposed GTME's, are calculated on the basis of the accepted phenomenological model and the obtained primary signals of information V_i. The formulas for these calculations, presented by the algorithm for the treatment of information specifically for calculating GTME coefficients (ATI-T), are given in Table 1. The calculations using this as well as all the subsequent algorithms of treatment of information (ATI) are purposely listed in sequence, i.e., the calculation of any parameter from its corresponding formula does not occur until all the necessary starting values of this formula have been determined in the preceding calculation steps.

The general representations of the linear thermodynamics of irreversible processes constituting the minimum of the required assumptions (a priori for our experiment) are the foundation for realizing the first two stages.

TABLE 3. Algorithm for Calculating Secondary ATV-V2 Parameters (weak magnetic field; nondegenerated carriers)

Calculation step	Secondary parameter	Formula for calculation	Parameters used	Literature cited
3.1	Dispersion law exponent r	$eA_{NE}^{\perp}\rho_0 R_H^{-1} k^{-1} + \frac{1}{2}$	R_H from (1.1) $A_{NE}^{\perp}$ from (1.2) ρ_0 from (1.3)	
3.2	Current carrier concentration n	$\frac{3\pi^{1/2}\Gamma(2r+3/2)}{4eR_H\Gamma^2(r+2)}$	R_H from (1.1) r from (3.1)	[4; 6]
3.3	Drifting mobility of current carriers u	$(\rho_0 en)^{-1}$	ρ_0 from (1.3) n from (3.2)	[4]
3.4	Electronic component of thermal-conductivity coefficient $\varkappa_e$	$\frac{k^2T(r+2)}{e^2\rho_0}$	ρ_0 from (1.3) r from (3.1)	[4]
3.5	Complete thermal-conductivity coefficient $\varkappa$	$\frac{A_{NE}^{\perp}}{A_E}T$	A_E from (1.7) $A_{NE}^{\perp}$ from (1.2)	[6]
3.6	Reduced Fermi level φ	$r+2-\left(r-\frac{1}{2}\right)\frac{9\pi u^2}{16A_{NE}^{\parallel}}\times$ $\times\left[\frac{\Gamma^2(2r+3/2)}{\Gamma^2(r+2)}-\frac{\Gamma(3r+1)}{\Gamma^3(r+2)}\right]$	$A_{NE}^{\parallel}$ from (1.12) r from (3.1) u from (3.3)	
3.7	Effective mass of current carriers m*	$\frac{h^2}{2\pi kT}\left[\frac{n}{2}\exp(-\varphi)\right]^{2/3}$	n from (3.2) φ from (3.6)	[4]
3.8	Relaxation time constant τ_0	$\frac{3um^*}{4\pi^{1/2}e\Gamma(r+2)}$	r from (3.1) u from (3.3) m^* from (3.7)	

The calculation of the secondary parameters is performed in the third stage according to the scheme presented in the diagram. Let us pause here at the three examples of using various semiconductor energy models (designated by the indices 1, 2, and 3) for calculating the investigated parameters.

As model 1 let us adopt the usual model of the kinetic phenomena in a solid, one which includes such assumptions as estimation of the relaxation time, simple spherical zones, one type of charge carriers characterized by a scalar effective mass. The intensity of the magnetic field remains arbitrary. Then the transfer equations [4] that include such parameters as μ_H, Π, $\varkappa$, σ_B, α', β', μ_E, and λ, serve as the original expressions for the charge and energy fluxes

$$\mathbf{j} = \sigma_B(\mathbf{E}^* - \alpha'\nabla T) + \sigma_B\mu_H[(\mathbf{E}^* - \beta'\nabla T), \mathbf{B}], \tag{1}$$

$$\mathbf{w} = \sigma_B\Pi(\mathbf{E}^* - \alpha'\nabla T) - (\varkappa_e + \varkappa_\phi)\nabla T + \mu_E[\sigma_B\Pi\mathbf{E}^* - \sigma\Pi\beta'\nabla T - \lambda\nabla T, \mathbf{B}], \tag{2}$$

The formulas for calculating these parameters and the Fermi level F from the primary parameters A_i can be obtained in this model from Eqs. (1) and (2); they comprise the ATI-V1 algorithm (Table 1). The formulas not marked with the literature references were obtained by the authors in the form convenient for calculating according to the proposed ATI-V.

In model 2, in addition to the assumptions in model 1 regarding the mixed character of conductivity and the quadratic law of dispersion, the following assumptions are added: the power dependence of relaxation time on the carrier energy

$$\tau(\varepsilon) = \tau_0\varepsilon^{r-1/2}; \tag{3}$$

the mechanism of carrier dispersion, the only one characterized by r and τ_0; nondegeneration of current carriers; and a weak magnetic field. As it is known [5], the criterion of a weak magnetic field, in the light of the assumptions made here, is the inequality

$$\mu_H^2B^2 \ll 1. \tag{4}$$

The secondary parameters that can be calculated by this model are the Fermi level F, the dispersion mechanism characteristics r and τ_0, and also concentration n which depends on r or F, the mobility u, the effective mass of carriers m*, and the electronic component $\varkappa_e$ of the complete thermal-conductivity coefficient $\varkappa$. The formulas for calculation are presented in Table 3 (ATI-V2 algorithm).

TABLE 4. Algorithm for Calculating Secondary ATI-V3 Parameters (weak magnetic field; degenerating carriers)

Calculation step	Secondary parameter	Formula for calculation	Parameters used	Literature cited
4.1	Carrier concentration n	$(eR_H)^{-1}\Phi_{3/2,\varphi}\Phi_{2r+\frac{1}{2},\varphi}\Phi_{r+1,\varphi}^{-2}$	R_H from (1.1) r and φ from (6),(7)	
4.2	Drifting mobility of current carriers u	$(en\rho_0)^{-1}$	n from (4.1) ρ_0 from (1.3)	[4]
4.3	Effective mass of current carriers m*	$\frac{h^2}{8kT}\left(\frac{3n}{\pi\Phi_{3/2,\varphi}}\right)^{2/3}$	n from (4.1)	[4]
4.4	Relaxation time constant τ_0	$um^*e^{-1}\Phi_{3/2,\varphi}\Phi_{r+1,\varphi}^{-1}$	u from (4.2) m^* from (4.3) r, φ from (6), (7)	
4.5	Electronic component of thermal-conductivity coefficient $\varkappa_e$	$\frac{k^2T}{e^2\rho_0}\left[\frac{\Phi_{r+3,\varphi}}{\Phi_{r+2,\varphi}}-\frac{\Phi_{r+2,\varphi}^2}{\Phi_{r+1,\varphi}^2}\right]$	ρ_0 from (1.3) r, φ from (6), (7)	[7]
4.6	Phonon component of thermal-conductivity coefficient $\varkappa_\Phi$	$\varkappa-\varkappa_e$	$\varkappa_e$ from (4.5)	[4]

The criterion of nondegeneration of the electronic gas, as it is known, is the inequality

$$F/kT = \varphi < -1. \tag{5}$$

Therefore, if the assumption made above is true, the obtained Fermi potential (3-6) must satisfy the inequality (5). Inasmuch as model 2 is a particular case of a more general model 1, the results pertaining to it must also be true for model 2. In particular, calculations of the Fermi level using 3-6 and 2-2 must be in agreement. It should be noted that for calculating a series of the most important parameters of Table 3 (namely, r, n, u, $\varkappa_e$, $\varkappa$) it is possible to be limited to the knowledge of galvanomagnetic effects.

Model 3 (Table 4) differs from model 2 only in the assumption on nondegeneration of the electronic gas. In this case the expressions for Fermi integrals, which enter into almost all formulas of the investigated parameters, are not simplified and the calculations must be performed in three stages. Two auxiliary values should therefore be calculated first from the formulas

$$\frac{\Phi_{r+2,\varphi}}{\Phi_{r+1,\varphi}} = A_N B^2 \frac{\varkappa e}{kT}, \quad \frac{\Phi_{2r+3/2,\varphi}}{\Phi_{2r+1/2,\varphi}} = \left(A_N B^2 + \frac{A_E \rho_0}{R_H}\right)\frac{\varkappa e}{kT}, \tag{6}$$

where $\Phi_{r,\varphi}$ is the Fermi integral determined from (7),

$$\Phi_{r,\varphi} = r\int_0^\infty \frac{x^{r-1}dx}{\exp(x-\varphi)+1}. \tag{7}$$

In order to perform calculations using formulas (6), additional measurement of the complete thermal-conductivity coefficient $\varkappa$ is required.

Parameters r and φ should subsequently be determined from (6) and (7) using numerical methods. The problem is simplified if the Fermi level is known in advance, for example, from (2-2).

Finally, from the known r and φ, with the aid of formulas given in the algorithm ATI-V3 (Table 4) one can find n, u, m*, and τ_0, and also separate $\varkappa_e$ and $\varkappa$.

Therefore, the proposed structure and organization for calculating the semiconductor parameters, through the use of the method of varying the influence factors permits simple and effective realization of the possibility of obtaining the largest amount of information in a single experiment and of fully automating the process of its treatment.

NOTATION

V_H and R_H are the voltage drops and coefficients of the Hall effect, respectively;

$V_{NE}^{\perp}$ and $A_{NE}^{\perp}$ are the Nernst–Ettinghausen (cross sectional) effect;

$V_{NE}^{\parallel}$ and $A_{NE}^{\parallel}$ are the Nernst–Ettingshausen (longitudinal) effect;
V_E and A_E are the Ettingshausen effect;
V_{RL} and A_{RL} are the Righi–Leduc effect;
V_N and A_N are the Nernst effect;
V_{MRL} and A_{MRL} are the Maggi–Righi–Leduc effect;
$V_{\Delta\rho}$ and H are the magnetic resistance effect;
ρ_0 is the specific resistance;
α is the thermal emf;
j is the current density;
w is the heat flux density;
B is the magnetic field induction;
E is the electric field intensity;
E* is $E - \nabla(F/e)$;
F is the Fermi level measured from the bottom of the conductivity band;
$\varkappa$ is the thermal-conductivity coefficient;
Π is the Peltier coefficient;
μ_H is the Hall mobility;
u is the drifting mobility;
τ_0 and r are the parameters of the exponent law of carrier dispersion;
σ_B is the electrical conductivity;
α' is the thermal emf in Hall current system;
β', μ_E and λ are the parameters in the transfer equations;

$$\beta' = \alpha + A_{NE}^{\perp}\mu_H^{-1};$$

$$\mu_E = \left(B^{-2} + \mu_H \frac{A_N}{A_E}\right)\left(\frac{A_N}{A_E} - \mu_H\right)^{-1};$$

$$\lambda = (A_{NE}^{\perp}\mu_H^{-1}\rho^{-1} - A_{RL}A_E^{-1})\,(1 + \mu_H B^2 A_N A_E^{-1})^{-1};$$

n is the current carriers' concentration;
m* is the effective mass of current carriers;
k is the Boltzmann constant;
h is the Planck constant;
e is the electron charge;
d and l are the dimensions of a specimen between the cross sectional (Hall) and the longitudinal probes, respectively.

Indices

0 signifies that B = 0.

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