THE KINETIC EFFECTS IN ANISOTROPIC SIZE-QUANTIZED n-Ge AND n-Si FILMS

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The behavior of kinetic coefficients depending on orientation of n-Ge and n-Si films surface is investigated at the presence of the nonquantized magnetic field. The general solution of transport equation and expressions for the relaxation time including various mechanisms of electrons scattering are obtained. Also the expressions for galvanomagnetic and thermomagnetic tensors are obtained at the arbitrary degree of electron gas degeneration and arbitrary value of transverse magnetic field. The Hall constant and thermopower in n-Ge and n-Si films plane in a strong magnetic field are calculated at various approximations of electron gas degeneration.

At the present time thin semiconducting films are intensively investigated in the size-quantized conditions that is connected with the microelectronics development. When the specimen sizes are of de Broglie wave length of the current carriers the quantum sized effects are occurred. In this case the quasi-discrete nature of energy spectrum appears and the form of wave functions changes. Some thermodynamic and kinetic properties for conducting films with standard band spectrum have been considered in the works [1-4]. In the works [5,6] the electron states in anisotropic size-quantized n-Ge and n-Si films have been considered and dependence of physical values on film surface orientation has been predicted, so-called the size-quantized anisotropy of thermodynamic properties of system. Evidently that such dependence also can be observed in kinetic characters of n-Ge and n-Si films.

In the present work the behavior of kinetic coefficients depending on orientation of n-Ge and n-Si films surface is investigated at the presence of the nonquantized magnetic field. The general solution of transport equation and expressions for the relaxation time including various mechanisms of electrons scattering are obtained. Also the expressions for galvanomagnetic and thermomagnetic tensors are obtained at the arbitrary degree of electron gas degeneration and arbitrary value of transverse magnetic field. The Hall constant and thermopower in n-Ge and n-Si films plane in a strong magnetic field are calculated at various approximations of electron gas degeneration.

1.The energy spectrum of electrons in the size-quantized n-Ge and n-Si films have the form [6]:

$$\varepsilon_s\left(n_s, k_x, k_y\right) = \frac{\hbar^2}{2m_{\parallel}}\left(\frac{\pi}{d}\right)^2 \varphi_s^2(\alpha) n_s^2 + \frac{\hbar^2}{2m_{\perp}}\left[\varphi_s^{-2}(\alpha) k_x^2 + k_y^2\right] , \qquad (1)$$

where $m_{\parallel}$ and $m_{\perp}$ are the longitudinal and transverse effective masses of electron respectively, d is the film thickness, s is the ellipsoid number, n_s=1,2,3,... is the sized quantum number, α is the angle of rotation of a normal to the [001] film surface, $\varphi_s(\alpha)$ are the functions that characterize the orientation of ellipsoids as regard to the system of reference and depend on anisotropy parameter of effective masses (see [6]).

To consider some kinetic characters of system it is necessary to solve the Boltzman transport equation. The solution of such equation in n-Ge and n-Si bulk specimens were obtained in the works [7,8]. As for size-quantized n-Ge and n-Si films we must to solve the two-dimensional transport equation on plane.

If represent the nonequilibrium distribution function of electrons in the form:

$$f_1 = \left(-\frac{\partial f_o}{\partial \varepsilon_s}\right)\left(\vec{V}\vec{P}\right) , \qquad (2)$$

and take into consideration that the external magnetic field is directed along a normal to the film surface then the next solution of equation is obtained:

$$\vec{P} = \frac{1}{1+\nu^2}\left\{\hat{\tau}\vec{\Phi}_o + \frac{e}{c}\hat{\tau}\left[\vec{H}\hat{M}^{-1}\left(\hat{\tau}\vec{\Phi}_o\right)\right]\right\} , \qquad (3)$$

where f_o is the function of Fermi-Dirac distribution $\nu = \frac{e|\hat{\tau}|^{\frac{1}{2}}}{c|\hat{M}|^{\frac{1}{2}}} H$, $\vec{\Phi}_o = -e\vec{E} - \frac{\varepsilon_s - \xi}{T}\vec{\nabla}T$, $\hat{\tau}$ is the tensor of relaxation time, $\hat{M}^{-1}$ is the inverse tensor of electron effective masses, $|\hat{\tau}|$ and $|\hat{M}|$ are determinants of the relaxation time and effective mass tensors respectively.

As we see from (2) and (3) $\vec{P}$ as the nonequilibrium distribution function depends on components of the relaxation time tensor. Therefore, to calculate the kinetic coefficients it is necessary obtain the expression for relaxation time at the different mechanisms of scattering. In our case $\vec{P}$ has two components that for each mechanism of scattering depend on only one relaxation time parameter τ_s.

The τ_s expression for electrons scattering on acoustical and non-polar optical phonons, point defects and impurity ions in film plane has the form:

$$\tau_s^{-1}\left(\varepsilon_s\right) = \sum_{\beta_s'} W_{\beta_s';\beta_s}\left(1 - \frac{k_x'k_x + \varphi_s^4(\alpha)k_y'k_y}{k_x^2 + \varphi_s^4(\alpha)k_y^2}\right), \qquad (4)$$

where $W_{\beta_s';\beta_s}$ is the probability of electron transition from state $\beta_s=(n_s, k_x, k_y)$ to state $\beta_s' = \left(n_s', k_x', k_y'\right)$ or back.

The exact calculations in cases of electron scattering on phonons and point defects give us:

$$\tau_s(\varepsilon_s) = \tau_0\varphi_s^{-1}(\alpha)\left(\overline{n}_s + \frac{1}{2}\right)^{-1}, \qquad (5)$$

where $\overline{n}_s = \left[\sqrt{\frac{\varepsilon_s}{\varepsilon_{1_s}}}\right]$ is an integer part of number $\sqrt{\frac{\varepsilon_s}{\varepsilon_{1_s}}}$, $\varepsilon_{1_s} = \varepsilon_s, (n_s = 1, k_x = k_y = 0)$, τ_0 are the multipliers that don't depend on energy and proportional to the analogous expressions for bulk specimen [7].

As it is seen from (5) τ_s depends on energy only through $\overline{n}_s$. Moreover, τ_s essentially depends on n-Ge and n-Si films surface orientation and in the $\overline{n}_s >> 1$ limit the result for bulk specimen is obtained.

In the case of electrons scattering on impurity ions the τ_s expression for arbitrary $\overline{n}_s$ values isn't obtained. However if take into consideration that the scattering is occurred without the transitions between the film subbands in this case for the relaxation time we obtain:

$$\tau_s(\varepsilon_s) = \tau_0\varphi_s^{-1}(\alpha)\left(\overline{n}_s + \frac{1}{2}\right)^{-1}\left(\varepsilon_s - \varepsilon_{n_s}\right)^2, \qquad (6)$$

where ε_{n_s} is the discrete part of the energy spectrum (1). Evidently in this case τ_s depends on energy through $\overline{n}_s$ and proportional ε_s^2.

2. Having known the solution of transport equation and expression for the relaxation time one can calculate the current and the energy flux densities and then we can determine the components of kinetic tensors. For the σ_{ik}, β_{ik} and χ_{ik} $(i, k = 1,2;\ i \le k)$ tensors that connect the current and the energy flux densities with the electric field and the temperature gradient the next expressions are obtained:

$$\sigma_{ik} = \frac{e^2 m_\perp}{\pi d\hbar^2}\left(-\frac{eH}{c}\right)^{k-i}\sum_{s=1}^{N}\left\{\varphi_s(\alpha)\sum_{n_s}\int_{\varepsilon_{n_s}}^{\infty}\frac{\left(\varepsilon_s - \varepsilon_{n_s}\right)\left(-\frac{\partial f_0}{\partial\varepsilon_s}\right)K_k(\varepsilon_s)K_{k-i}(\varepsilon_s)d\varepsilon_s}{1 + \nu^2(\varepsilon_s)}\right\}, \qquad (7)$$

$$\beta_{ik} = \frac{em_\perp}{\pi d\hbar^2 T}\left(-\frac{eH}{c}\right)^{k-i}\sum_{s=1}^{N}\left\{\varphi_s(\alpha)\sum_{n_s}\int_{\varepsilon_{n_s}}^{\infty}\frac{\left(\varepsilon_s - \varepsilon_{n_s}\right)\left(\varepsilon_s - \xi\right)\left(-\frac{\partial f_0}{\partial\varepsilon_s}\right)K_k(\varepsilon_s)K_{k-i}(\varepsilon_s)d\varepsilon_s}{1 + \nu^2(\varepsilon_s)}\right\}, \qquad (8)$$

$$\chi_{ik} = -\frac{m_\perp}{\pi d\hbar^2 T}\left(-\frac{eH}{c}\right)^{k-i}\sum_{s=1}^{N}\left\{\varphi_s(\alpha)\sum_{n_s}\int_{\varepsilon_{n_s}}^{\infty}\frac{\left(\varepsilon_s - \varepsilon_{n_s}\right)\left(\varepsilon_s - \xi\right)^2\left(-\frac{\partial f_0}{\partial\varepsilon_s}\right)K_k(\varepsilon_s)K_{k-i}(\varepsilon_s)d\varepsilon_s}{1 + \nu^2(\varepsilon_s)}\right\}, \qquad (9)$$

where $K_0=1$, $K_1(\varepsilon_s) = \frac{\tau_s(\varepsilon_s)}{m_\perp\varphi_s^2(\alpha)}$, $K_2(\varepsilon_s) = \frac{\tau_s(\varepsilon_s)}{m_\perp}$, $N=4$ (n-Ge) and $N=6$ (n-Si).

On the base of general expressions (7)-(9) for kinetic tensors we can calculate all kinetic effects in various conditions. Let us demonstrate some of them for a strong magnetic field ($\nu>>1$).

So, for the Hall constant in this case we obtain:

$$R_f = -\frac{1}{n_e ec}, \qquad (10)$$

where n_e is the concentration of electrons in film. Therefore in a strong magnetic field R_f doesn't depend on the film surface orientation, degree of degeneration of electron gas and mechanisms of scattering.

For the thermopower we have:

$$\alpha_f = -\frac{m_\perp k_0^2 T}{\pi d\hbar^2 en_e}\sum_{s=1}^{N}\left\{\varphi_s(\alpha)\sum_{n_s}\left[F_2(\eta_{n_s}) - \eta_{n_s}F_1(\eta_{n_s})\right]\right\}, \qquad (11)$$

where $F_r\left(\eta_{n_s}\right) = \int\limits_0^\infty x_s^r \left(-\frac{\partial f_o}{\partial x_s}\right) dx_s$ are the uni-parametric Fermi integrals of r index (r=1,2), $x_s = \frac{\varepsilon_s - \varepsilon_{n_s}}{k_o T}$, $\eta_{n_s} = \frac{\xi - \varepsilon_{n_s}}{k_o T}$.

Evidently in this case α_r doesn't depend on the mechanisms of scattering, but it depends on the film surface orientation, otherwise, the thermopower has so-called the size-quantized anisotropy.

In the case of degenerated electron gas for the α_r we obtain:

$$\alpha_r = -\frac{(\pi k_o)^2 T}{3en_e} g_r(\alpha \qquad , \tag{12}$$

where $g_r(\alpha) = \frac{m_\perp}{\pi d\hbar^2} \sum\limits_{s=1}^{N} \left\{\varphi_s(\alpha)\overline{n_s}\right\}$ is the density of electron states in film [6].

Therefore the α_r behavior in this case coincides with the density of states one near the Fermi energy. Otherwise, the thermopower depends on the film thickness as $1/d$ until the film subband doesn't coincide with the Fermi energy. In this case α_r changes by the jump and is equal the same value in bulk specimen. Therefore the thermopower in dependence on the film thickness has a saw-toothed character.

In the case of nondegenerated electron gas for α_r we have:

$$\alpha_r = -\frac{k_o}{e}\left\{2 - \ln\frac{\pi d\hbar^2 n_e}{m_\perp k_o T A(\alpha)} + \frac{B(\alpha)}{A(\alpha)}\right\}, \tag{13}$$

where $A(\alpha) = \sum\limits_{s=1}^{N}\left\{\varphi_s(\alpha)\sum\limits_{n_s} \exp\left(-x_{n_s}\right)\right\}$,

$B(\alpha) = \sum\limits_{s=1}^{N}\left\{\varphi_s(\alpha)\sum\limits_{n_s} x_{n_s} \exp\left(-x_{n_s}\right)\right\}$, $x_{n_s} = \frac{\varepsilon_{n_s}}{k_o T}$.

The α_r behaviour in this case in dependence on the film thickness is differed from the one in the degenerated statistics. The analysis of expression (13) show us that here $\alpha_r \sim \ln d + \frac{1}{d^2}$. Therefore the thermopower in this case also is a nonmonotonous function of film thickness. At the $\overline{n_s} \gg 1$ limit the result for bulk specimen independed on a film thickness is obtained.

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ÖLÇÜYƏ GÖRƏ KVANTLANMIŞ ANİZOTROP n-Ge VƏ n-Si NAZİK TƏBƏQƏLƏRİNDƏ KİNETİK EFFEKTLƏR

Kvantlanmamış maqnit sahəsində n-Ge və n-Si nazik təbəqələrində səthlərin səmtindən asılı olaraq kinetik əmsallar tədqiq olunur. Kinetik tənliyin ümumi həlli və müxtəlif səpilmə mexanizmləri əhatə edən relaksasiya zamanı üçün ifadələr alınmışdır. Eyni zamanda elektron qazının ixtiyari cırlaşma və eninə maqnit sahəsinin ixtiyari qiymətində qalvano- və termomaqnit tenzorlar üçün ifadələr alınmışdır. n-Ge və n-Si nazik təbəqələrin səthində güclü maqnit sahəsində elektron qazının müxtəlif cırlaşma yaxınlaşmalarda Holl əmsalı və termo-EHQ hesablanmışdır.

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КИНЕТИЧЕСКИЕ ЭФФЕКТЫ В АНИЗОТРОПНЫХ РАЗМЕРНОКВАНТОВАННЫХ ПЛЕНКАХ n-Ge И n-Si

В работе исследуется поведение кинетических коэффициентов в зависимости от ориентации поверхности пленок n-Ge и n-Si при наличии неквантующего магнитного поля. Получены общее решение кинетического уравнения и выражения для времени релаксации, охватывающие различные механизмы рассеяния. Получены также выражения для гальвано- и термомагнитных тензоров при произвольной степени вырождения электронного газа и произвольном значении поперечного магнитного поля. Вычислены коэффициент Холла и термоэдс в плоскости пленок n-Ge и n-Si в сильном магнитном поле при различных приближениях вырождения электронного газа.

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