

Kinetic processes in heavily doped semiconductor heterojunctions

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Abstract. We report results of study of electron - electron relaxation processes in the 2D electrons system with the fine structure of the energy spectrum and the spatial distribution of the electron density. For heavily doped heterojunction, when two subbands are filled, expressions for the time of intra- and inter-subband electron-electron interactions, matrix elements of a complete screening potential and the dielectric function were obtained beyond the long-wavelength limit. It is shown that the oscillations of temperature and concentration dependence of the electron - electron interactions are associated with the excitation of plasma oscillations components in 2D electron system.

1. Introduction

A number of experimental and theoretical studies of kinetic processes in low-dimensional semiconductor structures $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ [1-5] has discovered the small-angle oscillating dependence of the relaxation time τ_q on temperature T . These oscillations were observed for the heavily doped heterostructures ($n_s > 8.5 \cdot 10^{11} \text{ cm}^{-2}$), which are filled with main and second excited subband. The unique relationship of these anomalies with strong electron - electron interaction were established. An attempt to quantify the experimental curves $\tau_q(T)$ in the framework of existing theoretical concepts [6] was not successful. A qualitative explanation of the observed effects requires an examination of electronic interactions channels in complex 2D system of degenerate electrons. Using the method of self-consistent solution of the Poisson and Schrödinger equations [7], we found energy structure of the conduction band of the nanostructure and the spatial distribution of the electron density in the quantum-size levels. Figure 1 shows a typical nanostructure diagram for one of the samples with the filling of the two subbands, and the designation of the size quantization parameters used below.

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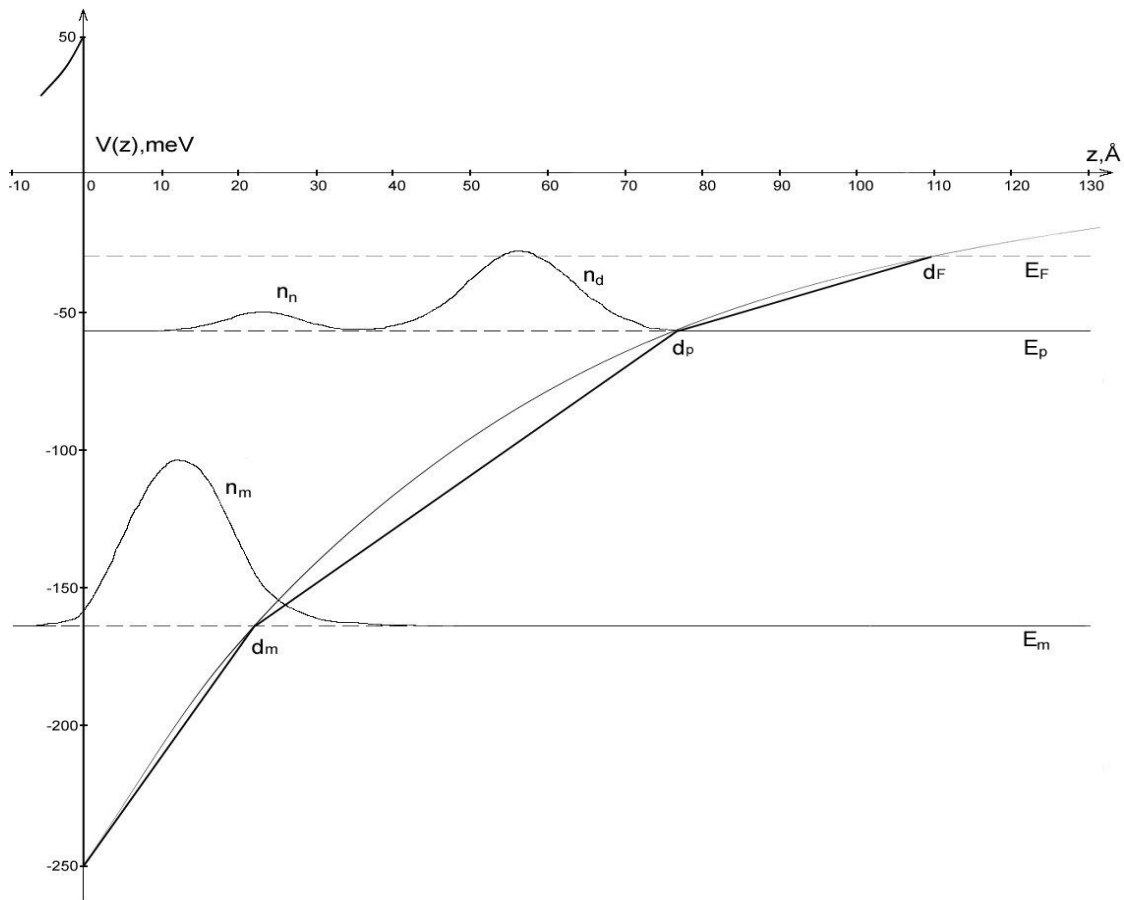


Figure 1. Diagram of the conduction band $V(z)$ of heterojunction with two occupied size-quantization subbands E_m and E_p ; n_m and $n_{n,d}$ — surface concentrations of 2D electrons, E_F — Fermi energy.

2. The matrix elements of the screening potential.

For a complete interaction Hamiltonian: $H = H_0 + H_{\text{int}}^{ijkl}$ with the field operators of creation and annihilation: $a_p^+(t) = \exp\left(-\frac{i}{\hbar} E(p)t\right) a_p^+$, $a_p(t) = \exp\left(-\frac{i}{\hbar} E(p)t\right) a_p$ we introduce one-particle fermion Green's function [7]:

$$G(p, t - t') = \frac{\langle T(a_p(t) a_p^+(t') S_\alpha(-\infty, \infty | g)) \rangle}{\langle S_\alpha(-\infty, \infty | g) \rangle} \quad (1)$$

with S - matrix:

$$S_\alpha(-\infty, \infty | g) = \sum_{n=0}^{\infty} \left(-\frac{i}{\hbar}\right)^n \frac{g^n}{n!} \int_{-\infty}^{+\infty} dt_1 \dots \int_{-\infty}^{+\infty} dt_n \times e^{\alpha(|t_1| + \dots + |t_n|)} T(H_{\text{int}}(t_1) \times \dots \times H_{\text{int}}(t_n)) \quad (2)$$

where $H_{\text{int}}(t) = \exp\left(-\frac{i}{\hbar} H_0 t\right) H_{\text{int}}$, H_0 - non - interaction Hamiltonian operator.

Then the probability of particle transition from pulses \mathbf{k} and \mathbf{p} in state $\mathbf{k} + \mathbf{q}$ and $\mathbf{p} - \mathbf{q}$ will be proportional to the integral of collisions [8]

$$\sum_{\mathbf{k}, \mathbf{p}} \delta(E_j(\mathbf{k} + \mathbf{q}) + E_l(\mathbf{p} - \mathbf{q}) - E_i(\mathbf{k}) - E_k(\mathbf{p})) f_{\mathbf{k}} f_{\mathbf{p}} (1 - f_{\mathbf{k}+\mathbf{q}}) (1 - f_{\mathbf{p}-\mathbf{q}}) \quad (3)$$

where f — Fermi-Dirac distribution function. The indices i, j, k, l are as follows: electron in a state i interacts with an electron in the state k whereby the transitions occur according to the states j and l .

Then the interaction Hamiltonian can be written as::

$$H_{\text{int}}^{ijkl}(t) = \sum_{\mathbf{q}} g(\mathbf{q}) V_{\text{tot}}^{ijkl}(\mathbf{q}, \omega) a_{\mathbf{p}+\mathbf{q}}^+(t) a_{\mathbf{p}}(t) + \sum_{\mathbf{p}_i, \mathbf{p}_j, \mathbf{q}_i, \mathbf{q}_j} V_{ijkl}(\mathbf{q}, \omega) \delta(\mathbf{p}_i + \mathbf{q}_i - \mathbf{p}_j - \mathbf{q}_j) a_{\mathbf{p}}(t) a_{\mathbf{p}+\mathbf{q}}^+(t) \quad (4)$$

In [2,6] an expression for the time of "e-e" interaction can be represented as:

$$\frac{1}{\tau_{ij}^{ee}} = \int_{-\infty}^{\infty} d\omega \sum_{k,m} \sum_{\mathbf{q}} |V_{\text{tot}}(\mathbf{q}, \omega)|^2 \sum_{\mathbf{k}, \mathbf{p}} \delta(E_j(\mathbf{k} + \mathbf{q}) + E_l(\mathbf{p} - \mathbf{q}) - E_i(\mathbf{k}) - E_k(\mathbf{p})) f_{\mathbf{k}} f_{\mathbf{p}} (1 - f_{\mathbf{k}+\mathbf{q}}) (1 - f_{\mathbf{p}-\mathbf{q}}) \quad (5)$$

where $V_{\text{tot}}(\mathbf{q}, \omega)$ — the matrix element of the full potential of shielding, which is the Fourier transform of the external potential screening $V_{\text{ext}}(\mathbf{r})$:

$$V_{\text{tot}}(\mathbf{q}, \omega) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} V_{\text{ext}}(\mathbf{r}) \exp[-(\mathbf{qr} - \omega t)] d^2\mathbf{r}. \quad (6)$$

In a Cartesian coordinate system, the expression for the external potential, double approximated triangular profile, will have such formula:

$$V_{\text{ext}}(z) = \begin{cases} \frac{E_1 - E_0}{d_m} z + E_0, & z < d_m, \\ \frac{E_2 - E_1}{d_p - d_m} (z - d_m) + E_1, & d_m < z < d_p, \\ \frac{E_F - E_2}{d_F - d_p} (z - d_p) + E_2, & d_p < z < d_F, \\ E_0 \exp\left[-z \frac{\ln(E_0 / E_F)}{d_F}\right], & z > d_F. \end{cases} \quad (7)$$

where $E_0 = V(0)$, $E_1 = V(d_m)$, $E_2 = V(d_p)$.

Thus, the solution to the problem of obtaining the analytical expressions for the relaxation time is reduced to calculation of the matrix elements of the screening for these types of interactions:

- 1) Intraband interaction, leading to transitions within the subbands (matrix elements V_{tot}^{mmmm} , V_{tot}^{pppp} , relaxation times τ_{mm}^{intra} , τ_{pp}^{intra}).
- 2) Intraband interaction, leading to transitions between subbands (matrix elements V_{tot}^{mmpm} , V_{tot}^{pmpp} , relaxation times τ_{mm}^{intra} , τ_{pp}^{intra}).
- 3) Intersubband interactions, leading to transitions within the subband (matrix elements V_{tot}^{mmpm} , V_{tot}^{pmpp} , relaxation times $\tau_{mm}^{\text{inter}} = \tau_{pp}^{\text{inter}}$).
- 4) Intersubband interactions, leading to transitions between subbands (matrix elements $V_{\text{tot}}^{mmpm} = V_{\text{tot}}^{pmpp}$, relaxation times $\tau_{mp}^{\text{inter}} = \tau_{pm}^{\text{inter}}$).

The intra and inter superscripts correspond to intra- and inter-subband interactions and identical or different subscripts denote transitions within or between subbands. Then we transform (6) to a more convenient form:

$$\frac{1}{\tau_{ij}^{ee}} = \int_{-\infty}^{\infty} \frac{d\omega}{\cosh^2(\hbar\omega/2k_B T)} \sum_{k,l} \sum_{\mathbf{q}} |V_{tot}^{ijkl}(\mathbf{q}, \omega)|^2 \chi_{ik}(\mathbf{q}, \omega) \chi_{jl}^*(\mathbf{q}, \omega) \quad (8)$$

where k_B - Boltzmann constant, polarizing function in the random phase approximation [9] is described by

$$\chi_{ik}(\mathbf{q}, \omega) = \frac{e^2}{q^2 n^2} \lim_{\alpha \rightarrow 0} \sum_{\mathbf{k}} \frac{f(\mathbf{k}) - f(\mathbf{k} + \mathbf{q})}{E(\mathbf{k} + \mathbf{q}) - E(\mathbf{k}) - \hbar\omega - i\hbar\alpha}. \quad (9)$$

Figure 2 illustrates the contributions of various mechanisms in the destruction of the Landau quantization, it shows the frequency dependence of the real and imaginary parts of the polarization function for different filling dimensional quantization subbands. It also illustrates the influence of the second subband filling degree on the spectrum of collective oscillations in 2D electron system. With increasing concentration n_m , the resonant frequency shifts to lower values in the temperature range 4-8 K.

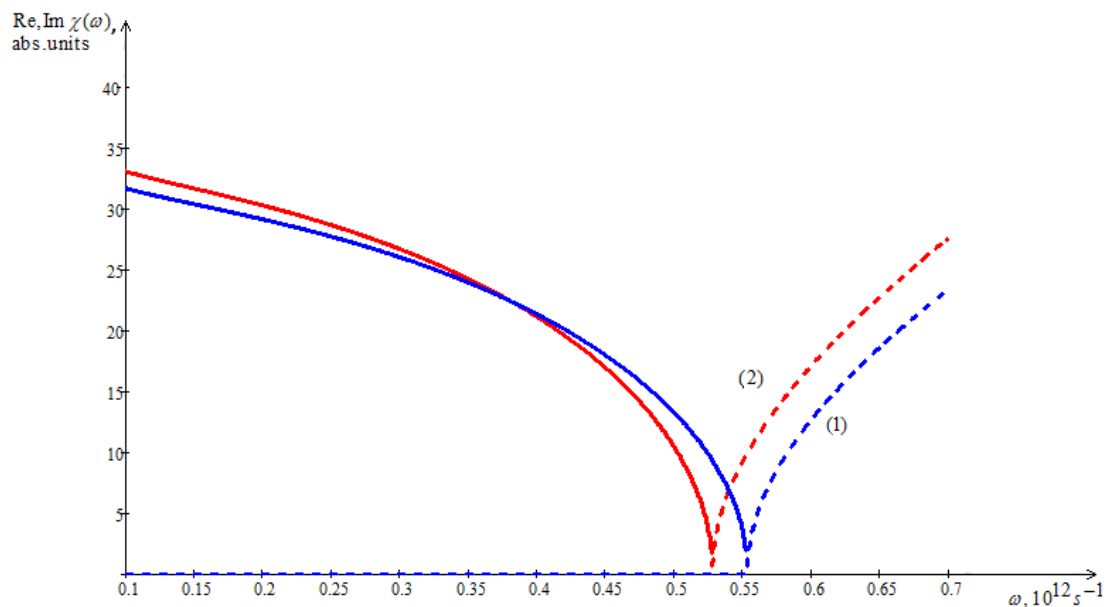


Figure 2. The frequency dependence of the polarization function for the main channel of interaction with the subband n -satellite: n_m : (1) – $9.1 \cdot 10^{11} \text{ cm}^{-2}$, (2) – 10^{12} cm^{-2} , $d_p/d_m = 3.5$. Solid curves – $\text{Re } \chi(\omega)$, dashed curves – $\text{Im } \chi(\omega)$.

It should be noted that each resonant frequency can be associated with the temperature at which the screening mechanism changes and the temperature dependence of the electron-electron interaction becomes non-monotonic. It is shown that the resonant frequency and temperature anomalies can be related as $\hbar\omega_{res} = kT$.

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