THE KINECTICS OF ENERGY RELAXATION IN QUANTUM WELLS IN A QUANTIZING MAGNETIC FIELD

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Abstract: The kinetics of the intraband relaxation of the electron energy in the system of Landau levels lying below the the optical phonon energy is studied. Unusual behaviour of the relaxation of electronic subsystem is found. Even though its main channel is the emission of optical phonons, the total relaxation time is several orders of magnitude higher than the characteristic scattering times on optical phonons.

Keywords: Energy relaxation; quantum well; Landau level; electron-electron scattering; optical phonon scattering.

1. Introduction

An investigation of relaxation processes in electron systems is a fundamental problem of solid- state physics, which is also of importance and interest for a wide range of applications. The character of these processes is determined by both the carrier scattering processes and the energy spectrum structure. While the relaxation processes have been well studied for the system of two-dimensional continuous subbands of quantum wells, this problem is still poorly understood for the system of Landau levels in quantum wells. In particular, there are some reports explaining the character of interlevel relaxation for the Landau levels lying below the optical phonon energy [1, 2].

In this paper, the kinetics of electron energy relaxation in the system of Landau levels below the optical phonon energy is considered. In this system, due to suppression of single-electron interband scattering (on impurities, heterointerface roughnesses, and acoustic phonons) in a quantizing magnetic field [3], the controlling mechanism of scattering between Landau levels is the electron-electron scattering. Since the total energy of electrons involved in an electron-electron scattering event remains unchanged, this mechanism leads only to electron redistribution over Landau levels but cannot cause system energy relaxation.

Furthermore, since one of electrons in the interlevel electron-electron scattering event always transfers to a higher level, a finite electron flux upward the Landau level ladder can arise. This can cause electron arrival at Landau levels arranged near or above the optical phonon energy and, hence, optical phonon emission.

The description of the electron redistribution over Landau levels, thus the relaxation is complicated by the impossibility of introducing the fixed time of electron-electron scattering from the Landau level since it strongly depends on its population and the population of other levels. This entails the necessity of solving the self-consistent kinetic problem: the electron distribution over Landau levels is defined by scattering times, whereas these times themselves are defined by the electron distribution over levels [3-5].

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These circumstances can lead to a rather extraordinary pattern of system energy relaxation. In the next section we present the results of calculations of the time evolution of the electron distribution over Landau levels during their selective excitation to one of levels lying below the optical phonon energy. Different from work [2], in which electrons transiting to the neighboring Landau levels play main role in the kinetics, here we take into account all possible transitions due to intra- and intersubbands electron-electron scattering.

2. Theoretical background

In this paper, we consider the electron relaxation kinetics in Landau level system in the n-type GaAs/AlGaAs quantum well in a quantizing magnetic field $\mathbf{B} = B\mathbf{e}_z$ perpendicular to structure layers. Initially, the quantum well is in the thermodynamic equilibrium state. At the initial time, instantaneous intrasubband excitation of a fraction of electrons to the Landau level lying below the optical phonon energy occurs. Then the time evolution of level populations is traced by solving the system of balance equations [1 - 3] between electron arrival at the level and electron escape from the level due to two-particle electron-electron scattering events and emission of longitudinal optical phonons,

$$\begin{aligned}\frac{dN_i}{dt} = \sum_{j,f,g} W\begin{pmatrix} f & g \\ i & j \end{pmatrix} N_f N_g \left[1-\frac{N_i}{\alpha}\right]\left[1-\frac{N_j}{\alpha}\right] - \sum_{j,f,g} W\begin{pmatrix} i & j \\ f & g \end{pmatrix} N_i N_j \left[1-\frac{N_f}{\alpha}\right]\left[1-\frac{N_g}{\alpha}\right] \\ + \sum_f \left\{ \frac{1}{\tau_{f\to i}^{LO}} N_f \left[1-\frac{N_i}{\alpha}\right] - \frac{1}{\tau_{i\to f}^{LO}} N_i \left[1-\frac{N_g}{\alpha}\right] \right\}\end{aligned} \quad (1)$$

Here, N_i is the two-dimensional electron density on the Landau level i (level population), $\alpha = \frac{1}{\pi\ell^2}$ is the Landau level degeneracy factor, and $\ell = \sqrt{\frac{\hbar c}{eB}}$ is the magnetic length. The rates of electron-electron scattering W and longitudinal optical phonon (LO) emission are given by the expressions, calculated by the Fermi rule [6,7]

$$W\begin{pmatrix} f & g \\ i & j \end{pmatrix} = \frac{2}{\alpha^2 L^2} \sum_{\substack{k_i,k_j \\ k_f,k_g}} \frac{4\pi}{\hbar} \left|V_{(i,f)(g,j)}(k_i,k_j,k_f,k_g)\right|^2 \delta(E_i + E_j - E_f - E_g) \quad (2)$$

and

$$\frac{1}{\tau_{i\to f}^{LO}} = \frac{2}{\alpha L^2} \sum \frac{2\pi}{\hbar} \left|H^{LO}(k_i,k_f,\mathbf{q})\right|^2 \delta(E_i - E_f - \hbar\omega_{LO}) \,. \quad (3)$$

Where

$$V_{(i,f)(g,j)}(k_i,k_j,k_f,k_g) = \int d\mathbf{r}_1 d\mathbf{r}_2 \psi_f^*(\mathbf{r}_1,k_f)\psi_i(\mathbf{r}_1,k_i) \frac{e^2}{\varepsilon_s \left|\mathbf{r}_1 - \mathbf{r}_2\right|^2} \psi_g^*(\mathbf{r}_2,k_g)\psi_j(\mathbf{r}_2,k_j) \,, \quad (4)$$

ε_s is the static permittivity,

$$H^{LO}(k_i,k_f,\mathbf{q})=\int d\mathbf{r}\,\psi_f^*(\mathbf{r},k_f)\hat{\mathbf{H}}^{LO}\psi_i(\mathbf{r}_1,k_i)\,, \tag{5}$$

$$\hat{\mathbf{H}}^{LO}=\left[2\pi\hbar\omega_{LO}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_s}\right)\frac{e^2}{V}\right]^{1/2}\left[1+N_B(\hbar\omega_{LO})\right]^{1/2}i\,\frac{\exp(-i\mathbf{qr})}{q}\,, \tag{6}$$

ω_{LO} is the LO-phonon frequency, ε_∞ is the high-frequency permittivity, $V=L^3$ is the sample volume, $N_B(x)=\left[\exp\left(\frac{x}{k_BT}\right)-1\right]^{-1}$ is the Boltzmann distribution function. The finite width of the Landau levels is taken into account by replacing the δ-function in equation (2) and (3) by form-factors $F^{e-e}(E_i+E_j-E_f-E_g)$ and $F^{LO}(E_i-E_f-\hbar\omega_{LO})$ respectively, which are approximated by Lorentzian

$$F^{e-e}(E)=\frac{1}{\pi}\frac{\Gamma_{e-e}}{E^2+\Gamma_{e-e}^2}\,;\;F^{LO}(E)=\frac{1}{\pi}\frac{\Gamma_{LO}}{E^2+\Gamma_{LO}^2}\,. \tag{7}$$

Halfwidths Γ_{e-e} = 2 meV and $\Gamma_{LO}=\sqrt{2}$ meV are typical values for quantum well structures [8, 9].

In the parabolic approximation, the single-electron wavefunctions and energy levels are given by the expressions [10]

$$\psi(x,y,z)=\frac{\exp(ikx)}{\sqrt{L}}\varphi_\nu(z)\Phi_n(y-k\ell_\perp^2) \tag{8}$$

and

$$E_{(\nu,n)}=\varepsilon_\nu+\hbar\omega_C\left(n+\tfrac{1}{2}\right). \tag{9}$$

Where ε_ν and $\varphi_\nu(z)$ are the ν-th subband energy and the corresponding wavefunction, respectively; $\Phi_n(y)$ is the wavefunction for the nth energy level of the linear harmonic oscillator of the cyclotron frequency $\omega_C=\frac{eB}{m_wc}$; and m_w is the effective mass in the quantum well.

3. Relaxation kinetics in Landau level system

We illustrate the relaxation dynamics by the example of a GaAs/$Al_{0.3}Ga_{0.7}As$ quantum well 15 nm wide with doping level $N_d=10^{10}cm^{-2}$ in magnetic field B = 3,5 T. At such a magnetic field, six Landau levels ($n=0-5$) of the lower subband are below the optical phonon energy. We create the nonequilibrium population in the system under study by selective electron excitation from the ground state ($n=0$) to one of Landau levels, e.g., $n=3$ level, i.e., only $n=0$ and $n=3$ Landau levels are populated at the initial time. Without loss of generality we choose $N_0(\mathrm{t}=0)=8\cdot10^{10}cm^{-2}$ and $N_3(\mathrm{t}=0)=2\cdot10^{9}cm^{-2}$.

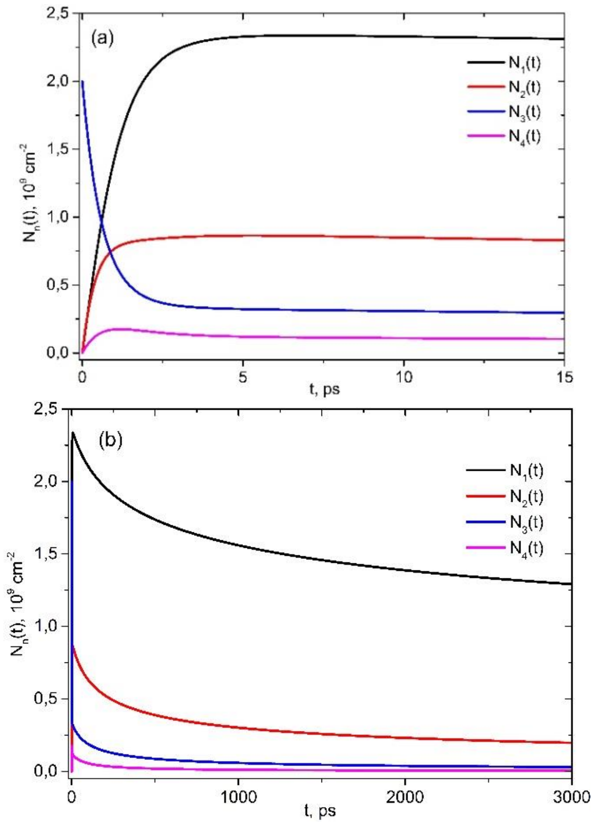

Figure 1: *The numerical calculated kinetics of Landau level populations in the first subband in the GaAs/*$Al_{0.3}Ga_{0.7}As$ *quantum well 15 nm wide with doping level* $N_d = 10^{10} cm^{-2}$ *in magnetic field B = 3,5 T.*

The time evolution of Landau level populations for this situation is shown in Fig. 1. We can see that the system relaxation process consists of two stages. In the first short (~ 5 picoseconds) stage (Fig. 1a), electron redistribution over Landau levels occurs due to electron-electron scattering. As a result, the electronic subsystem is thermalized with establishing a Boltzmann-type distribution with temperature $T_e \sim 70$ K greatly exceeding the lattice temperature (4,2 K - in liquid helium). It is important that the electron redistribution over Landau levels occurs almost without changing the total energy of the electronic subsystem. Therefore the electronic subsystem under study is quasi-closed and the established temperature is defined by the total energy of the excitation and weakly depends on its nature.

During the second stage, the electron density at excited Landau levels slowly decreases (Fig. 1b).), however, at each time point, the electron distribution over levels remains Boltzmann. The electronic subsystem temperature decreased (Fig. 2), i.e. the electronic subsystem cools. The total relaxation time is greater than 10^3ps which exceeds the thermalization time defined by electron-electron scattering processes and the optical phonon emission time (which is 0.1 ps in the system under study) by several orders of magnitude.

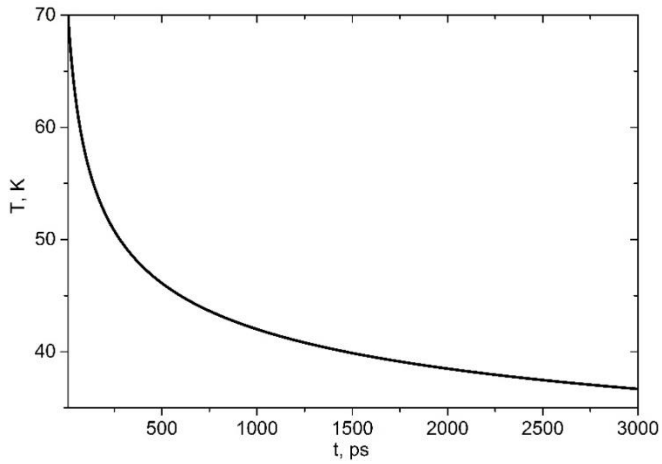

Figure 2: *Time dependence of the electronic subsystem temperature*.

Thus, the energy relaxation pattern in the system of discrete Landau levels qualitatively differs from the relaxation in the two-dimensional continuous subband of the quantum well, during which relaxation and thermalization processes are almost inseparable.

Since the population of the n = 5 Landau level lying immediately below the optical phonon in the steady-state distribution is small, but finite, an electron flux from this level to the overlying one ($n \geq 6$) arises due to electron-electron scattering. When electrons have reached these levels, they emit optical phonons, thus transferring energy to the lattice. As a result, exactly the phonon emission from levels lying above the optical phonon results in the system energy relaxation

4. Conclusion

The Landau level system in the quantum well exhibits an extraordinary mechanism of excitation energy relaxation in the electronic subsystem, in which scattering processes of two types are involved. First, these are electron-electron scattering processes which lead to both the electronic subsystem without changing its energy and the electron transport to Landau levels lying near or above the optical phonon energy. Second, these are processes of optical phonon emission from these levels, due to which the electronic subsystem energy is transferred to the lattice. Such relaxation character results in the relaxation times that are longer than characteristic scattering times in the system under consideration by several orders of magnitude.

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TÓM TẮT

ĐỘNG HỌC QUÁ TRÌNH HỒI PHỤC NĂNG LƯỢNG TRONG GIẾNG LƯỢNG TỬ ĐẶT TRONG TỪ TRƯỜNG LƯỢNG TỬ HÓA

Đoàn Thế Ngô Vinh, Nguyễn Thành Công
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Trong bài báo này chúng tôi nghiên cứu động học của quá trình hồi phục năng lượng của các electron trong hệ các mức Landau nằm bên dưới mức năng lượng phonon quang học. Diễn biến bất thường của quá trình hồi phục năng lượng kích thích của hệ con electron được phát hiện. Mặc dù trên thực tế kênh chính của quá trình này là phát xạ phonon quang học, nhưng thời gian hồi phục năng lượng lớn hơn thời gian tán xạ trên phonon quang học vài bậc của lũy thừa mười.

Từ khóa: Hồi phục năng lượng; giếng lượng tử; mức Landau; tán xạ electron-electron; tán xạ phonon quang.