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ENERGY RELAXATION IN TWO-DIMENSIONAL ELECTRON GaS IN InGaAs/InP VIA ELECTRON–ACOUSTIC PHONON INTERACTION

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The energy relaxation in two-dimensional electron gas in $In_{0.53}Ga_{0.47}As$/InP has been studied in a wide range of electron temperatures (from 0.1 to 10 K). The energy loss rate of electrons is controlled by the interaction of electrons with the piezoelectric potential of acoustic phonons. The value of the piezoelectric constant for InGaAs lattice-matched to InP is deduced from theoretical fits of the experimental data: $h_{14} = (1.1 \pm 0.1) \times 10^7$ V/cm. Available data for the piezoelectric constant of $In_xGa_{1-x}As$ are discussed in the light of the results of this work.

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1. Introduction

Electron–phonon interaction is one of the fundamental processes in solids. Although it is well characterized in bulk semiconductors, its understanding in low-dimensional and disordered systems is limited.

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Here we present the results of our experimental study of the electron–phonon interaction in a two-dimensional electron gas (2DEG) in $In_{0.53}Ga_{0.47}As/InP$ at very low temperatures [1]. Most of the previous measurements reported in the literature were done on GaAlAs/GaAs [2–6], except for one paper on InGaAs/InP [7].

At low temperatures the electrons do not possess a sufficient energy to emit optical phonons and their energy loss rate is controlled by their interaction with the acoustic phonons. In this particular case the energy balance equation can be written in terms of power functions of the electron and lattice temperatures [8, 9]

$$Q_{\mathrm{eph}} = \alpha(T_{\mathrm{e}}^{\gamma} - T_{\mathrm{L}}^{\gamma}), \tag{1}$$

where Q_{eph} is the power transferred from the electron system with the electron temperature T_{e} to the crystal lattice with the temperature of the lattice T_{L}. The parameter α depends on the elastic constants of the matrix, on the coupling constants and also on the 2DEG density.

The values of the characteristic exponent γ figuring in Eq. (1) are different but unique for different types of electron–phonon interaction, and are collected in Table I [1, 8, 9].

TABLE I

Theoretical values of the exponent γ in the energy balance equation for different types of the electron–acoustic phonon intaraction.

Type of scattering	$T_{\mathrm{e}} \ll T_{\mathrm{K}}$		$T_{\mathrm{e}} \gg T_{\mathrm{K}}$
	$T_{\mathrm{e}} \ll T_{\mathrm{s}}$	$T_{\mathrm{e}} \gg T_{\mathrm{s}}$	
Piezoelectric acoustic phonon	$\gamma = 5$	$\gamma = 3$	$\gamma = 1$
Deformation potential acoustic phonon	$\gamma = 7$	$\gamma = 3$	$\gamma = 1$

$T_{\mathrm{K}} = hv_{\mathrm{sound}}k_{\mathrm{F}}/(\pi k_{\mathrm{B}})$, $T_{\mathrm{s}} = hv_{\mathrm{sound}}/(2\pi^{3/2}a_{\mathrm{B}}k_{\mathrm{B}})$.

2. Experimental methods and results

The samples were liquid phase epitaxially grown $In_{0.53}Ga_{0.47}As/InP$ heterostructures [10, 11]. The electron density and mobility determined from the period of Shubnikov–de Haas oscillations and from the low field Hall resistivity were $(0.3–1.5) \times 10^{11}$ cm^{-2} and $(1–6.5) \times 10^{4}$ cm^2/(V s), respectively (see Table II). Low-temperature mobility in these structures is limited by alloy scattering and as a rule it is much lower than in similar AlGaAs/GaAs structures.

To study the electron–phonon interaction the standard electron heating method was used, with the resistivity of the sample serving as an electron thermometer. Resistivity was measured by the four-terminal method using ac voltage (f = 14 Hz) superimposed on a dc voltage. This dc voltage was used to supply heating Joule power to the 2DEG. The experiments were performed in the temperature range from 40 mK to 20 K, using a He3–He4 dilution refrigerator for the lowest temperatures. The samples were placed into the dilution chamber and had a good thermal contact with liquid He.

From the temperature dependence of the ac resistance with zero dc voltage, and from the measurement of the ac resistance versus the Joule power supplied by sweeping the dc voltage, the equation of the energy balance of the electrons

TABLE II

Parameters of the samples and results of theoretical fits to the experimental data.

Sample	n_s [cm^{-2}]	$\mu_{4.2\,K}$ [cm^2/(Vs)]	$T = 0.1 \div 0.4$ K		$T = 0.5 \div 1.2$ K		$T = 1.9 \div 5$ K	
			γ	h_{14} [V/cm]	γ	h_{14} [V/cm]	γ	h_{14} [V/cm]
C347	0.36×10^{11}	1.6×10^4	5	1.03×10^7	3	1.06×10^7		1.1×10^7
C96	0.95×10^{11}	6.3×10^4					1	1.1×10^7
C165	1.15×10^{11}	4.2×10^4			3	1.25×10^7	1	1.1×10^7

$Q_{\mathrm{eph}}(T_e, T_L)$ was obtained for different lattice temperatures in the range from 0.1 to 4 K and electron temperatures in the range from 0.1 to 10 K. The representative results are shown in Fig. 1 using coordinates corresponding to Eq. (1).

3. Discussion

The analysis of our experiments on the basis of the energy balance equation of the 2DEG (Eq. (1)) has shown that there exist three temperature ranges, in each of which a different type of electron–phonon interaction dominates (see Table II). The γ exponents obtained experimentally show that the energy balance of the 2DEG is controlled by the interaction with the piezoelectric potential of the acoustic phonons. In each temperature range, fitting the appropriate theoretical formulas to the data, the value of the piezoelectric constant (h_{14}) was deduced (Table II).

For the lowest temperatures, $0.1 < T_e < 0.4$ K, $\gamma \cong 5$, (see Fig. 1a), which corresponds to the interaction with screened phonons. In the intermediate range, $0.5 < T_e < 1.2$ K, $\gamma \cong 3$ (see Fig. 1b), which corresponds to small angle scattering. Finally, for the highest temperatures, $1.8 < T_e < 10$ K, $\gamma \cong 1$ (see Fig. 1c), which corresponds to quasi-elastic scattering of electrons on acoustic phonons.

Based on the data in Table II it is possible to describe the experimental results in all temperature ranges with an averaged value of the piezoelectric constant $h_{14} = (1.1 \pm 0.1) \times 10^7$ V/cm.

Because the piezoelectric effect produces an important contribution to the transport effects, it is of practical importance to establish the values of the relevant coupling coefficients defined as $e_{14} = \varepsilon_r \varepsilon_0 h_{14}$ in a function of the indium content x in the $In_xGa_{1-x}As$ alloy system. The literature data are very scarce in this respect, and they are collected in Fig. 2 [12–17], together with our present result for $x = 0.53$.

Data for the binary end compounds were deduced from direct measurements of the piezoelectric constants using acoustic methods [13]. For GaAs a higher value was obtained from theoretical fits to the low field mobility versus temperature data [14]. Our experimental result for the composition $x = 0.53$ roughly fits the expected linear interpolation between the end compounds. However the only other data from the literature for composition around $x = 0.15 \div 0.25$ [15–17] are lying markedly lower. However, these latter values were deduced from photocurrent measurements on InGaAs/GaAs multi-quantum well (MQW) p–i–n diodes.

The scarcity of data as well as the obvious discrepancy between the results obtained by different methods prompt further studies in this field.

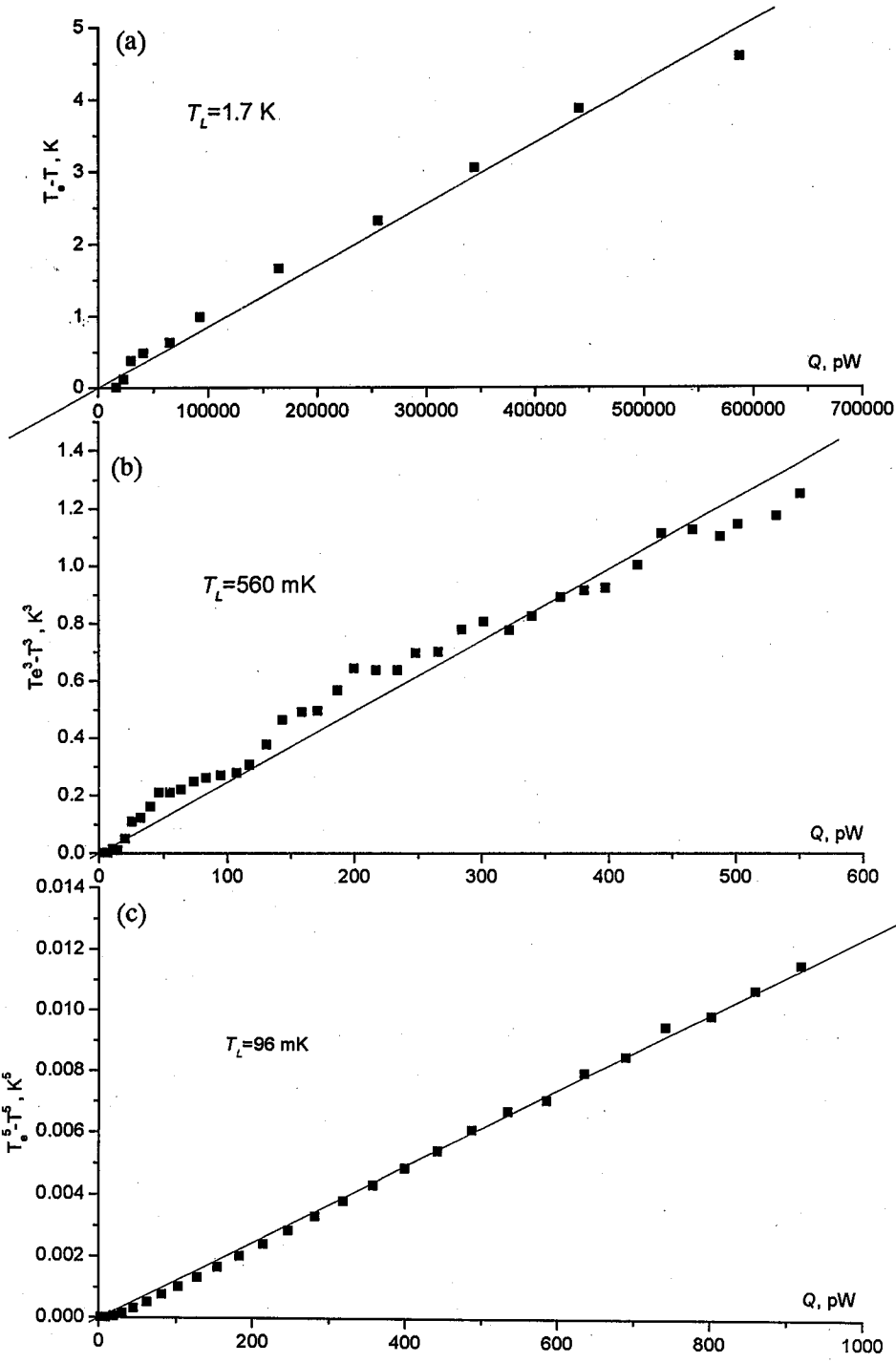

Fig. 1. Fit of Eq. (1) to the experimental data in different temperature ranges, each one characterized by different electron–acoustic phonon interaction mechanism.

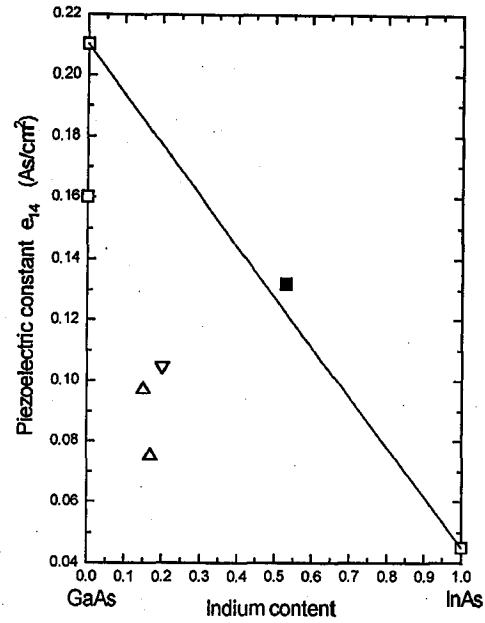

Fig. 2. Piezoelectric constant (e_{14}) versus the indium content in $In_xGa_{1-x}As$. Open squares — data for the end compounds [13, 14], full square — our data, down triangle — data from Ref. [15], up triangles — data from Refs. [16, 17].

4. Conclusions and acknowledgments

The energy relaxation of 2DEG with low density in $In_{0.53}Ga_{0.47}As/InP$ heterostructures has been studied in a wide range of the electron temperatures from 0.1 to 10 K. It has been shown experimentally that the energy balance of the 2DEG can be written in the form $Q_{\rm eph} = (T_{\rm e}^{\gamma} - T_{\rm L}^{\gamma})$.

It has been found that the energy balance of 2DEG is controlled by the interaction with piezoelectric potential of the acoustic phonons. There exist three ranges of temperatures, in each of which a different type of the electron–phonon interaction dominates. A fit, based on appropriate theoretical models, allows us to describe the experimental results in all ranges using one unique value of the piezoelectric constant $h_{14} = (1.1 \pm 0.1) \times 10^7$ V/cm.

Literature data for the piezoelectric constant of $In_xGa_{1-x}As$ were discussed in the light of the deduced value of the piezoelectric constant for indium composition $x = 0.53$.

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