Phonon-Drag Images of GaAs and AlAs Quantum Wells

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Abstract. In the presented (first) study we analyze the changes in the phonon-drag patterns of AlAs and GaAs quantum wells as a function of well thickness. Our numerical calculations include the phonon focusing, the acoustic anisotropy of the electron-phonon coupling and the conduction-band anisotropy. From such analysis, in connection with future systematic experimental studies, one can draw information about the electron-phonon coupling parameters and the effective mass of the electrons. A domination of electron-phonon interaction by deformation potential coupling in narrow AlAs quantum wells is shown. A comparison of our numerical results with recent phonon-drag measurements of an AlAs quantum well shows very good agreement.

1. Introduction
Phonon-drag imaging is considered as a powerful tool for analyzing the fundamental properties of low-dimensional electron systems [1]. The ability to isolate phonons of particular polarization and propagation direction is a decisive advantage of the method. This allows, e.g., a direct insight into the fundamental electron-phonon coupling processes. In the past, phonon-drag imaging experiments, as well as theory, were concentrated on low-dimensional electrons in GaAs [2-5]. Now, there is an increasing interest in systems where the electrons are confined in AlAs layers. However, two-dimensional (2D) electrons in AlAs have some unique properties that are very different from those in GaAs. They occupy multiple conduction-band minima at the X-points of the Brillouin zone and have a large and anisotropic effective mass in contrast to the much lighter and isotropic mass in GaAs. Due to their higher effective mass electrons in AlAs interact more strongly with phonons than electrons in GaAs. Depending on the well thickness or application of in-plane strain, different conduction-band valleys can be occupied. As a consequence we deal with a system with tunable valley degeneracy and Fermi contour anisotropy [6].

In the phonon-drag measurements described above, the electric current is induced in the 2D electron system by pulses of (nonequilibrium) acoustic phonons and is mapped as a function of the phonon source position. The resulting phonon-drag images are therefore a convolution of phonon propagation (focusing) in the sample and the probability that a current is induced by the phonons hitting the low-dimensional electron system. Consequently, to interpret such experiments it is
necessary to use theoretical models for the propagation and interaction of the phonons, which include the effects of acoustic anisotropy as well as the effect of electron confinement.

2. Model of phonon-drag imaging in AlAs quantum wells

In bulk GaAs electrons occupy the Brillouin zone $Γ$-point conduction band valley. The electrons in this valley have an isotropic effective mass $m^* = 0.067 m_0$, where $m_0$ is the free electron mass. The electronic structure of AlAs is more complex. Electrons in bulk AlAs occupy the Brillouin zone $X$-point conduction band valleys. The electrons in these valleys have a highly anisotropic effective mass (longitudinal $m^*_\text{long} = 1.1 m_0$, transverse $m^*_\text{trans} = 0.2 m_0$). Therefore, the band minimum has a threefold degeneracy (excluding spin degeneracy) and the constant energy surfaces consist of three (six half) ellipsoids labeled by the directions of their major axes: $X_0$, $X_0$, and $X_0$ for the [100], [010] and [001] valleys, respectively. However, if we are interested in the electronic structure of (quasi-)2D electrons in AlAs quantum wells (QWs), the situation is different. The degeneracy of the $X$ valleys is lifted due to the confinement of the electrons and strain. In the case of AlAs QWs with a well thickness less than approximately 5 nm grown on a (001) AlGaAs substrate, the two $X$ valleys (along $±[001]$) are occupied since the larger effective mass of the electrons along the confinement direction lowers their energy. The result is a 2D electron system with an isotropic and relatively small effective mass $m^* = m^*_\text{trans} = 0.2 m_0$ (like in GaAs QWs). In contrast, in the case of a larger well thickness the $X_0$ and $X_0$ valleys (having their major axes in the plane of the 2D electrons) are occupied. This happens as a result of a biaxial compression induced by the lattice mismatch between the GaAs substrate and the AlAs layer. Consequently, the 2D electron system has an anisotropic Fermi contour and a much heavier average effective electron mass $m^* = (m^*_\text{trans} \cdot m^*_\text{long})^{1/2} = 0.46 m_0$. By application of a symmetry breaking strain in the sample plane it is additionally possible to change the population in the two different $X_0$ and $X_0$ valleys.

We study the properties of the 2D electron system in both the GaAs QW and the AlAs QW with the help of the phonon-drag imaging method. In a typical experiment a small QW structure on one side of the AlGaAs substrate is irradiated with nonequilibrium acoustic phonon pulses generated in a laser-heated spot on the other side of the substrate. The phonons absorbed in the QW transfer their in-plane quasimomentum $\hbar \mathbf{q}_\parallel$ to the 2D electrons and the resulting phonon-drag current is mapped as a function of the laser spot position. Therefore, the phonon-drag images can be interpreted as a convolution of phonon focusing in the substrate (describing the angular dependence of the magnitude of the incoming phonon signal in the QW) and the probability that a current will be induced by the phonons in the 2D electron system. Thus the time integrated drag current is proportional to

$$\int_{-\infty}^{\infty} dt \hat{j}_d(t, \mathbf{r}) \sim \sum_{\mathbf{q}, \lambda} \sum_{\nu} q_{\nu, \lambda} \cdot N_{\mathbf{q}, \lambda}(\mathbf{r}) \left[ |h_{\mathbf{q}, \lambda}^{(\text{DP})}|^2 + |h_{\mathbf{q}, \lambda}^{(\text{PE})}|^2 \right] \cdot \left| G(q_z) \right|^2 \cdot \text{Im} \chi^*(q_1, \omega_{q, \lambda}),$$

where we sum over all $X_0$ (with $\nu = x, y, z$) and over all phonon modes with phonon wave-vector $\mathbf{q}$, polarization $\lambda$, and frequency $\omega_{q, \lambda}$. $N_{\mathbf{q}, \lambda}(\mathbf{r})$ is the time integrated (nonequilibrium) phonon distribution function in the electron system depending on the relative position $\mathbf{r}$ of phonon source and electron system and on the properties of the phonon source. The overlap integral $G(q_z)$ follows from the electron confinement. $\text{Im} \chi^*(q_1, \omega_{q, \lambda})$ is the imaginary part of the dynamic susceptibility of the interacting 2D electron system in the valley $X_0$. The electron-phonon coupling includes both the deformation potential (DP) interaction

$$|h_{\mathbf{q}, \lambda}^{(\text{DP})}|^2 = \frac{\hbar}{2 e_0 \omega_{q, \lambda}} \left( \sum_{j=x,y,z} (\Theta_j + \delta_j, \Theta_j)(\mathbf{e}_{q, \lambda}, q_j) \right)^2$$
(in AlAs depending on the valley index $v$, while in GaAs $\Theta_u = 0$) and the piezoelectric (PE) scattering

$$|p_{q,\lambda}^{(DP)}|^2 = (2 |e| h)^2 \frac{h}{2 \rho \omega} \left( q_x q_y (e_{q,\lambda})_z + q_y q_z (e_{q,\lambda})_x + q_z q_x (e_{q,\lambda})_y \right)^2,$$

where $e_{q,\lambda}$ is the polarization vector of the phonons, $\Theta_d$, and $\Theta_u$ are the deformation potential constants and $h_{14}$ is the piezoelectric coupling constant. Our numerical calculations include the phonon focusing in the substrate, the acoustic anisotropy of the electron-phonon coupling, the conduction-band anisotropy and the geometry of phonon source and detector (for details of the phonon drag and focusing calculations see [3, 5] and the references therein).

3. Comparison to experiment
In the Figs. 1 and 2 we compare the experimental image of phonon-drag induced in a (001) AlAs QW [7] with the results of corresponding numerical calculations. In the 15 nm wide QW used here the $X_x$ and $X_y$ valleys are occupied. All parameters in our calculations correspond to the values of the experiment. The phonon source is of Planckian type (laser), the scanning area is $1.5 \times 1.5 \text{ mm}^2$, the active area of the 2D electron system is $30 \times 30 \text{ µm}^2$, the thickness of the substrate is 0.5 mm and the density of the 2D electrons is $4.5 \cdot 10^{15} \text{ m}^{-2}$.

Figure 1. Experimental phonon-drag image of a 15 nm AlAs QW (from [7]).

Figure 2. Calculated phonon-drag image of a 15 nm AlAs QW.

The white and black spots in the figures correspond to opposite directions of the induced current. Both in the measured image and in the calculated image the strong phonon signal and the sign inversion close to the central square shaped structure are particularly striking. Contrary to the interpretation in [7] we relate these features to the anisotropy of the DP electron-phonon interaction and to the contribution of DP coupled transverse polarized phonons. The agreement of our numerical results with the experimental drag image confirms the correctness of our calculations.

4. Numerical results
Figure 3 (a-f) shows the calculated patterns of the phonon-drag current induced in AlAs QWs of different well width and of different valley occupancy. In all cases we have assumed nonequilibrium phonon beams of Planckian type spectrum. The density of the quasi-2D electrons is taken as $4.5 \cdot 10^{15} \text{ m}^{-2}$. Each point of the 2D maps corresponds to a respective position of the phonon source.
The phonon source is moved in the (001) plane on the bottom side of the substrate and the scan from left to right covers the angular range (−56°, + 56°) of phonon propagation. The central point of each image corresponds to the [001] direction. The diagonals of the images run along [100] and [010] and the drag current is calculated in [110] direction. Positive and negative signals are represented as bright and dark shades, respectively, while the average gray tone corresponds to zero signal.

**Figure 3.** Calculated phonon-drag patterns: (a-c) for a 15 nm AlAs QW (X_x and X_y valleys are occupied) and (d-f) for a 5 nm AlAs QW (X_z valley is occupied). In patterns (a) and (d) both PE and DP interactions are taken into account, patterns (b) and (e) are for PE coupling only and patterns (c) and (f) are for DP interaction only.

**Figure 4.** Calculated phonon-drag patterns for a 15 nm GaAs QW. In pattern (a) both PE and DP interactions are taken into account, pattern (b) is for PE coupling only and patterns (c) is for DP interaction only.
The patterns presented in Figure 3 (a-c) are for a AlAs QW of well thickness equal to 15 nm (X\textsubscript{x} and X\textsubscript{y} valleys are occupied) while the patterns (d-f) correspond to a well thickness equal to 5 nm (X\textsubscript{z} valley is occupied). In the patterns (a) and (d) both the PE and the DP electron-phonon interactions are taken into account. For comparison, in the patterns (b) and (e) only the contribution of the PE coupling is presented, while the patterns (c) and (f) include only the contribution of the DP interaction. The absolute value of the calculated drag current differs between different patterns by orders of magnitude. So the patterns are not in the same scale. However, a qualitative analysis remains possible.

In Figure 4(a) the phonon-drag image for a 2D electron system in a 15 nm wide GaAs QW is presented. Due to the much lower effective mass of the electrons in the GaAs QW the calculated drag-current is at least by a factor 10 smaller compared to the current in a corresponding 15 nm wide AlAs QW (Figure 3(a)). This fact is also confirmed by measurements [7].

Comparing the patterns (a)-(c) of Figure 3 it follows that in the case of a 15 nm wide AlAs QW both the DP and PE interactions contribute approximately equally to the resulting phonon-drag image. However, the contribution of the DP interaction is stronger as in the case of a GaAs QW (Figure 4(a)). Surprising are the results presented in the patterns (d)-(f) of Figure 3 (5 nm wide AlAs QW, where the X\textsubscript{z} valley is occupied). In this case the in-plane effective mass and the Fermi contour are isotropic and resemble those in GaAs QWs. So, one may expect that the corresponding patterns (Figure 3(d) and Figure 4(a)) are similar. However, in the case of the 5 nm wide AlAs QW the contribution of the DP coupled transverse polarized acoustic phonons strongly dominates, while in the case of the GaAs QW the PE interaction is dominating. We relate this phenomenon to the strong anisotropy of the DP electron-phonon interaction in the AlAs QWs. However, this result needs a more detailed study and discussion. In all patterns of the AlAs QWs we observe large contribution from transverse polarized acoustic phonons coupled by DP interaction. Thereby, this contribution seems to be particularly significant in such systems.

5. Conclusions
We have presented a preliminary theoretical study of how phonon drag patterns of AlAs QWs change as a function of well thickness and valley occupancy. We have compared these patterns with corresponding patterns of GaAs QWs. The results show that phonon-drag measurements can give direct information about the effective mass, the electron-phonon coupling parameters and the valley occupancy of 2D electrons in quantum wells. We have obtained a very good agreement between our numerical results and a first experimental image and we are able to explain the peculiarities of the phonon signal in the measured patterns. The domination of the DP electron-phonon interaction in AlAs QWs is shown.

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