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Phonon-drag images of AlAs quantum wells: the effect of well thickness and effective mass anisotropy

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Abstract. We present a first theoretical study of how phonon drag patterns of AlAs quantum wells change as function of well thickness and valley occupancy. Our numerical simulations include the phonon focusing, the acoustic anisotropy of the electron-phonon coupling and the conduction-band anisotropy. From such an analysis, in connection with future systematic experimental studies, one can draw information about the effective mass and the electron-phonon coupling parameters. A comparison of our numerical results with a first experimental drag image of an AlAs well shows very good agreement. The main features of the experimental image can be explained.

1. Introduction

It is well established that phonon spectroscopy techniques, like phonon-drag imaging, can be a powerful tool for analyzing the fundamental properties of low-dimensional electron systems [1]. Phonon-drag images allow, e.g., a direct insight into the electron-phonon coupling processes because of the ability to isolate phonons of particular polarization and propagation direction. In the past, such 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. 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 large and anisotropic effective masses. 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. This results in a system with tuneable effective mass, Fermi contour anisotropy and valley degeneracy, i.e., in a system with rich and new physics [6].

In phonon-drag studies we are interested in, an electric current is induced by direct momentum transfer from the ballistic phonon pulses to the low-dimensional electrons. To interpret such measurements it is important to use theoretical models for the propagation and interaction of the nonequilibrium acoustic phonons which include the effect of acoustic anisotropy as well as the effect of electron confinement.
2. Model of phonon-drag imaging in AlAs quantum wells

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 $m^*_{\text{long}} = 1.1m_0$, transverse $m^*_{\text{transv}} = 0.2m_0$). The band minimum has therefore a three-fold degeneracy (excluding spin degeneracy) and the constant energy surfaces consist of three (six half) ellipsoids denoted by the directions of their major axes: $X_x$, $X_y$, and $X_z$ 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 confinement and strain. In an AlAs QW with well thickness less than approximately 5 nm grown on a (001) GaAs substrate, the two $X_z$ valleys (along $\pm[001]$) are occupied because the larger effective mass of electrons along the confinement directions lowers their energy. The result is a 2D electron system with an isotropic and relatively small effective mass $m^* = m^*_{\text{transv}} = 0.2m_0$. In contrast, for larger well thicknesses the $X_x$ and $X_y$ valleys with their major axes lying in the plane are occupied. The reason is a biaxial compression induced by the lattice mismatch between GaAs and AlAs. The result is a 2D electron system with an anisotropic Fermi surface and a much heavier average effective electron mass $m^* = (m^*_{\text{transv}} \cdot m^*_{\text{long}})^{1/2} \approx 0.46m_0$. It is possible to change the population in the two different valleys $X_x$ and $X_y$ (along $\pm[100]$ and $\pm[010]$, respectively) by application of a symmetry breaking strain in the sample plane.

The interaction of the electrons in the AlAs QW with the phonons is studied with the help of phonon-drag imaging. In a typical experimental setup a small AlAs QW structure on one side of the 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 AlAs QW are transferred 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 an convolution of phonon focusing in the substrate (describing 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

$$
\int_{-\infty}^{\infty} dt \overline{j}_i(t, \vec{r}) \sim \sum_{\nu} \sum_{\vec{q}, \lambda} \overline{q}_\parallel : N_{\vec{q}, \lambda}(\vec{r}) \cdot \left( |h^{\nu \chi}_{\vec{q}, \lambda}(\vec{r})|^2 + |h^{\nu \chi}_{\vec{q}, \lambda}(\vec{r})|^2 \right) \cdot |G(q_z)|^2 \cdot \text{Im} \chi^\nu(\overline{q}_\parallel, \omega_{\vec{q}, \lambda}) ,
$$

where we sum over all occupied valleys $X_\nu$ (with $\nu = x, y, z$) and over all phonon modes with phonon wavevector $\vec{q}$, polarization $\lambda$ and frequency $\omega_{\vec{q}, \lambda}$. $N_{\vec{q}, \lambda}(\vec{r})$ is the time integrated (nonequilibrium) phonon distribution in the electron system determined by the position and the properties of the phonon source as well as by the phonon focusing in the GaAs substrate. The overlap integral $G(q_z)$ follows from the electron confinement. For a QW of thickness $L_A$ we obtain

$$
|G(q_z)|^2 = \left[ \frac{\pi^2}{2} \right]^2 \cdot \left[ \frac{\sin \frac{\pi L_A}{2 q_z}}{\sin \frac{\pi L_A}{2}} \right]^2 .
$$

$\text{Im} \chi^\nu(\overline{q}_\parallel, \omega_{\vec{q}, \lambda})$ is the imaginary part of the dynamic susceptibility of the interacting 2D electrons in the valley $X_\nu$. The electron-phonon coupling in AlAs includes both deformation potential (DP) interaction

$$
|h^{\nu \chi}_{\vec{q}, \lambda}(\vec{r})|^2 = \frac{\hbar}{2p \omega_{\vec{q}, \lambda}} \left( \sum_{j=x,y,z} (\Theta_d + \delta_{v j} \Theta_v) \langle \vec{e}_{\vec{q}, \lambda} \rangle_j q_j \right)^2
$$

and the metric potential (MP) interaction

$$
|h^{\nu \chi}_{\vec{q}, \lambda}(\vec{r})|^2 = \frac{\hbar}{2p \omega_{\vec{q}, \lambda}} \left( \sum_{j=x,y,z} (\Theta_d + \delta_{v j} \Theta_v) \langle \vec{e}_{\vec{q}, \lambda} \rangle_j q_j \right)^2
$$
(depending on the valley) and piezoelectric (PE) scattering

\[
|h_{q, \lambda}^{(PE)}|^2 = (2|e|h_{14})^2 \frac{\hbar}{2\rho V \omega_{q, \lambda}} \left( q_x q_y (\vec{e}_{q, \lambda})_z + q_y q_z (\vec{e}_{q, \lambda})_x + q_z q_x (\vec{e}_{q, \lambda})_y \right)^2 ,
\]

where \(\vec{e}_{q, \lambda}\) is the polarization vector of the phonons. \(\Theta_d, \Theta_u\) and \(h_{14}\) are the corresponding deformation potential and piezoelectric coupling constants, respectively. Our numerical simulations include therefore 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. Numerical results

Figs. 1-3 show the calculated patterns of phonon-drag current induced in (001) AlAs QWs of different well width and valley occupancy by beams of monochromatic phonons of frequency 240 GHz. The density of the quasi-2D electrons is in all cases \(4.5 \cdot 10^{15} \text{ m}^2\). 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 corresponds to an angular range in phonon propagation of \(-56^\circ \ldots +56^\circ\). The center of the image corresponds to the [001] direction. The diagonals of the images run along [100] and [010] and the drag current is measured in [110] direction. Positive and negative signals are represented as dark and bright shades, an average grey tone corresponds to zero signal. In Fig. 4, for comparison, 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 obtained drag-signal is at least a factor 10 smaller. This fact is also confirmed by measurements [7]. The strong suppression of the phonon-drag signal for large in-plane components of phonon wavevector in the images of the 5 nm AlAs QW (Fig. 1) and of the GaAs QW (Fig. 4), compared to the 15 nm wide AlAs QW (Fig. 3), is also caused by the differences in the effective masses. A large anisotropy is visible in the image of the 15 nm QW where only the \(X_x\) valley is occupied (Fig. 2). This is the result of the highly anisotropic Fermi surface. In all patterns of the AlAs QWs we observe large contributions from phonons coupled by DP interaction, thereby the contribution of the DP coupled transverse polarized acoustic phonons is particularly significant.

Figure 1. Phonon-drag image of a 5 nm AlAs QW (only \(X_z\) valley is occupied).

Figure 2. Phonon-drag image of a 15 nm AlAs QW under strain (only \(X_x\) valley is occupied).

Figure 3. Phonon-drag image of a 15 nm AlAs QW (\(X_x\) and \(X_y\) valleys are occupied).
4. Comparison to experiment

In the Figs. 5 and 6 we compare a first experimental image of phonon-drag induced in a (001) AlAs QW [7] with a corresponding numerical simulation. In the 15 nm wide QW used here the $X_x$ and $X_y$ valleys are occupied. All parameters in the calculations correspond to the values of the experiment. The phonon source is of Planckian type (laser), the scanning area is $1.5 \times 1.5$ mm$^2$, the active area of the 2D electron system is $30 \times 30$ $\mu$m$^2$, the thickness of the substrate is 0.5 mm, the electron density $4.5 \times 10^{15}$ m$^{-2}$.

The strong phonon signal and the sign inversion close to the central square shaped structure are particularly striking in both the measured and the calculated image. Contrary to the interpretation in [7] we can explain these features as a consequence of the anisotropy of the DP electron-phonon interaction and of the contribution of DP coupled transverse polarized phonons.

5. Conclusion

We have presented a first theoretical study of how phonon drag patterns of AlAs QWs change as function of well thickness and valley occupancy. The results show that it is possible to obtain by phonon-drag measurements direct information about the effective mass, the electron-phonon coupling parameters and the valley occupancy of 2D electrons in AlAs quantum wells. There is 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 pattern.

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