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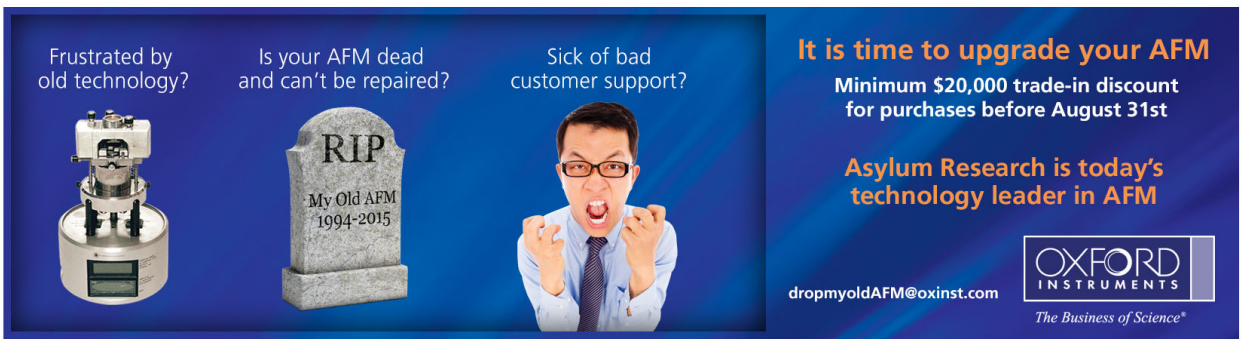

Γ to X_z electron transfer times in type-II superlattices due to emission of confined phonons

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We calculate the $\Gamma \rightarrow X_z$ electron transfer times due to the emission of confined longitudinal optical phonons in type-II GaAs-AlAs and AlGaAs-AlAs superlattices. A dielectric continuum model is employed to describe the electron-confined-phonon interaction and the electron envelope wave functions are obtained from a Kronig–Penney model. The calculated transfer times compare within order of magnitude, or better, with available experimental results and we obtain a good qualitative description of the transfer time dependence on the layer thicknesses.

Carrier dynamics in semiconductor heterostructures has attracted considerable attention in the last few years due to its importance to both fundamental physics and device applications. The hot carrier relaxation in type-I quantum wells and superlattices is reasonably well understood, yet there is little under understanding of the carrier dynamics in type-II superlattices.

In AlGaAs-AlAs superlattices the Γ states in the AlGaAs layers can be made higher in energy than the X states in AlAs layers by an appropriate choice of Al concentrations and layer thicknesses. Thus, the superlattice becomes indirect in real space, i.e., a type-II superlattice. Furthermore, the bulk X_z valley folds onto the Γ_{SL} point of the superlattice minizone while the $X_{x,y}$ valleys fold onto the M_{SL} point[1,2] and the superlattice will be direct in the reciprocal space, except when the $X_{x,y}$ valleys are lower in energy than the X_z valley.[3] The optical transitions associated with the X_z valley are termed as *pseudodirect* (i.e., weakly allowed direct) by some authors[4,5] who have observed these transitions in photoluminescence and photoreflectance measurements. Strictly speaking this is valid only if the number of monolayers in a superlattice period is even. If this number is odd then the bulk X_z point will not fold onto the minizone Γ_{SL} point. However, in the following we will assume that the bulk X_z folds always onto the Γ_{SL} even if the nominal number of superlattice period of the samples studied is odd, keeping in mind that there is always some uncertainty in the measurement of this number.

Electrons are mainly photoexcited into the Γ states of a type-II superlattice, but they scatter rapidly to the lower lying X states. This fast transfer has been observed in time-resolved absorption measurements by Saeta *et al.*[6] and Feldmann *et al.*[7,8] Also, de Paula *et al.*[9] have measured GaAs confined and interface phonons associated with the electron transfer to X_z using time-resolved anti-Stokes Raman scattering.

So far, there has been little effort to determine theoretically the $\Gamma \rightarrow X_z$ electron transfer times in type-II superlattices. Recently, Stroscio, Dutta, and Zhang[10] presented calculations of electron-interface-phonon transition probability amplitudes. However, they do not present calculations of the resulting scattering times.

In this letter we present theoretical calculations of the $\Gamma \rightarrow X_z$ electron transfer times in type-II GaAs-AlAs and AlGaAs-AlAs superlattices due to the emission of confined phonon modes (Fröhlich interaction). The bulk X_z folding onto the minizone Γ_{SL} point indicates that a $\Gamma \rightarrow X_z$ electron transfer involves phonons with small wave vectors and thus the dominant electron-phonon interaction will be the Fröhlich interaction. This is confirmed by the Raman measurements[9] that probes only phonons with small wave vectors. Deformation potential can thus be ruled out for the $\Gamma \rightarrow X_z$ electron transfer, nonetheless it can still be important for the $\Gamma \rightarrow X_{x,y}$ electron transfer. We obtain an order of magnitude agreement with available experimental measurements,[6–9] and an excellent qualitative agreement for the transfer time dependence on the layer thicknesses.[8]

Calculations of intersubband scattering rates[11] and carrier capture rates[12] due to confined phonons for type-I quantum wells and superlattices provided a good description of experimental results. In this work we extend the theoretical model of electron-confined-phonon interaction to the case of a $\Gamma \rightarrow X_z$ electron transfer mediated either by GaAs or AlAs longitudinal optical (LO) confined phonons, i.e., LO-GaAs or LO-AlAs confined phonons. Using an analogy with the intersubband calculations on type-I structures: we replace the lower lying type-I Γ subbands with the type-II X_z subbands, remembering that the X_z folds onto the Γ_{SL} point. The transfer can thus be treated in a similar way as a type-I intersubband transition.

In order to describe the superlattice electron envelope wave function we use a Kronig–Penney model[13] and do not consider the Γ-X mixing. The available effective-mass theoretical models include the Γ-X mixing phenomenologically either by adjusting experimental results[14] or by comparing with more elaborate theoretical calculations.[15,16] There is, so far, little consensus about the most adequate way to describe the mixing by a simple effective mass theory. For the time being we prefer to present our calculation without including the Γ-X mixing and thus avoid any adjustable parameters. Figure 1 displays the electron envelope wave functions for the first Γ and X_z states and their overlap for a 20 Å-40 Å GaAs-AlAs superlattice. Also shown are the overlaps of the wave functions with the first confined phonon amplitude taken as $\sin(2z\pi/L)$ (for the electron-confined-phonon interaction we use the corrected slab model.[17]) Note that the Γ

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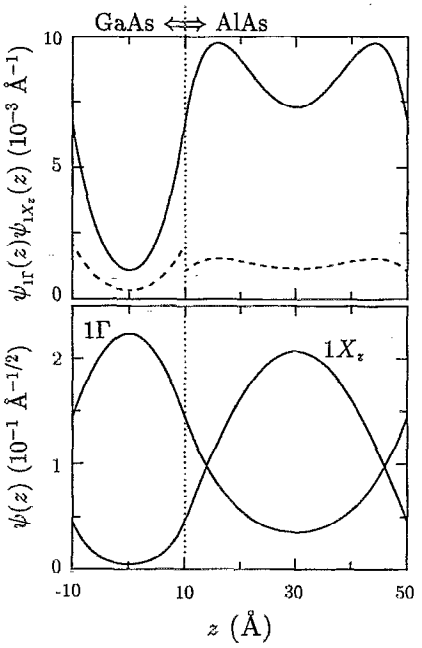

FIG. 1. Overlap of the 1Γ and $1X_z$ wave functions, shown in the lower part of the figure, as a function of the position in the superlattice. The dashed curve is the overlap of these two wave functions times the amplitude of the first confined phonon mode (either LO-GaAs or LO-AlAs).

wave function penetrates more into the AlAs layer than the X_z wave function into the GaAs layer, thus the overlap is larger in the AlAs layer than in the GaAs layer. The Γ and X barrier heights and the bulk Γ GaAs and X AlAs conduction

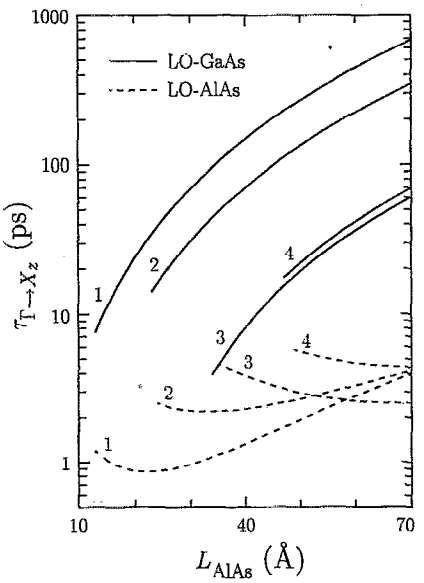

FIG. 2. Calculated $\Gamma\to X_z$ electron transfer times as a function of the AlAs layer thickness for superlattices with fixed GaAs layer thickness of 23 Å. The full (dashed) curves show the transfer times due to LO-GaAs (LO-AlAs) confined phonons. The labels indicate the final X_z state, e.g., a number 3 means a transition from the first Γ state in GaAs to the third X_z state in AlAs.

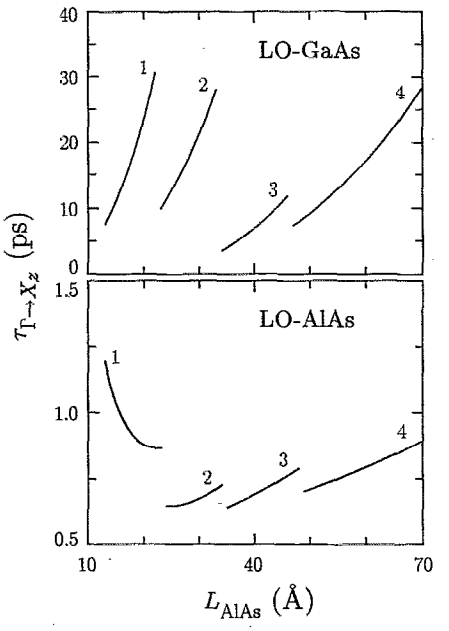

FIG. 3. Calculated $\Gamma\to X_z$ electron transfer times as a function of the AlAs-layer thickness for superlattices with fixed GaAs-layer thickness of 23 Å. The upper (lower) part of the figure shows the transfer times due to LO-GaAs (LO-AlAs) confined phonons. The labels indicate the total number of transitions involved, e.g., a number 3 indicates that transitions from the first Γ state in GaAs to all three lower lying X_z states in AlAs are considered.

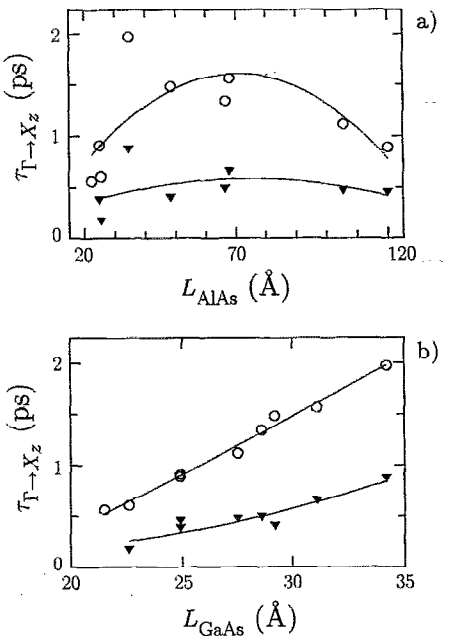

FIG. 4. Calculated $\Gamma\to X_z$ electron transfer times (hollow circles) for the GaAs-AlAs samples described by Feldmann *et al.* (Ref. 8) (samples 1–9). Part (a) displays the transfer times with respect to the AlAs layer thickness (but also with varying GaAs layer thickness) and part (b) with respect to the GaAs layer thickness (also varying AlAs layer thickness). The experimental results for samples 2–9 (at $T=10$ K) are indicated as full triangles (Ref. 20). The curves are a second order regression through the points and are shown to illustrate the general behavior of the transfer times.

TABLE I. Calculated (τ_{calc}) and experimentally (τ_{exp}) determined transfer times for $Al_xGa_{1-x}As$-AlAs superlattices (samples 10–12 from Ref. 8).

Sample	x	L_{GaAs} (Å)	L_{AlAs} (Å)	τ_{calc} (ps)	τ_{exp} (ps)
10	0.4	99.9	50.1	3.5	1.9
11	0.36	110.4	94.8	2.9	4.3
12	0.37	193.3	102.7	13.0	22.0

band offset used in our calculations are 1047, 316, and 145 meV, respectively. We considered a 35%–65% band alignment and used the bulk energy gaps from Landolt–Börnstein.[18] For further parameters used in our calculation see Ref. 11.

In Fig. 2 we present the $\Gamma \rightarrow X_z$ electron transfer times for GaAs-AlAs superlattices. We show separately the several possible transitions from Γ to the nth X_z subband as a function of the AlAs layer thickness with a fixed GaAs layer thickness of 23 Å. The transfer times due to LO-AlAs confined phonons are found to be much faster than those due to LO-GaAs confined phonons. This is mainly due to the larger wave function overlap in the AlAs layer (see Fig. 1) and a larger Fröhlich coupling strength for AlAs. The total electron transfer times for the same phonon mode are presented in Fig. 3. The transfer time due to LO-GaAs confined phonons are in the range of 5–30 ps whereas the transfer time due to LO-AlAs confined phonons are in the range of 0.5–1.5 ps. The measured transfer time due to LO-GaAs confined phonons for a 23 Å-41 Å GaAs-AlAs superlattice is about 1 ps,[9] which is at the same order of magnitude compared to the calculated value of 7 ps.

In Fig. 4 we show the calculated total electron transfer times (LO-GaAs plus LO-AlAs) for the GaAs-AlAs samples studied by Feldmann *et al.*[8] Calculated transfer times are higher roughly by a factor of 2 than the measured ones, however there is an excellent qualitative agreement for the layer thicknesses dependence. The transfer times for the AlGaAs-AlAs samples are shown separately in Table I. For samples 11 and 12 the calculated transfer times are smaller than the measured ones. This happens because the contribution of the LO-GaAs confined phonons are larger due to the larger AlGaAs layer.

We calculated also the electron transfer times for the 22.6 Å-71 Å and 31.2 Å-71 Å GaAs-AlAs samples studied by Saeta *et al.*,[6] the calculated (measured) times are 0.7 ps (0.1 ps) and 1.6 ps (0.4 ps), respectively. Again there is a rough agreement between calculated and measured transfer times.

In view of the absence of adjustable parameters in our calculation, this rough quantitative agreement and the good qualitative description of the layer thickness dependence can be considered as a theoretical evidence that indeed the $\Gamma \rightarrow X_z$ electron transfer is mediated by a Fröhlich interaction. We should point out that in this calculation we are not considering the mixing of Γ and X_z states and also the interface phonon modes are not taken into account yet. An electron-phonon interaction theory strongly depends on the overlap of the initial and final wave functions, in our case Γ and X_z, and therefore the inclusion of the Γ-X_z mixing is expected to enhance this overlap and consequently reduce the transfer times. The inclusion of interface phonon modes are also expected to reduce the overall transfer times, however, it is known from type-I calculations[19] that the contribution of confined phonons to the intersubband scattering times are more important than interface phonons.

In conclusion, we have presented theoretical results of $\Gamma \rightarrow X_z$ electron transfer times for GaAs-AlAs and AlGaAs-AlAs type-II superlattices. We find a rough quantitative agreement with measured transfer times and a good qualitative description of the layer thicknesses dependence. This can be considered as a theoretical evidence that the $\Gamma \rightarrow X_z$ electron transfer is due to electron-phonon Fröhlich interaction.

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[20] Table I of Ref. 8 shows no data for sample 1 at $T=10$ K, however in their Fig. 5 where the $T=10$ K data are displayed there is a point corresponding to the value listed in the table for sample 1 at $T=295$ K. For this reason we chose not to display any data for sample 1 in our Fig. 4.