

Tunability of electron spin coherence in III–V quantum wells

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We have calculated both T_1 and T_2 for (110)-oriented GaAs/AlGaAs quantum wells near room temperature. The altered symmetry of (110)-oriented quantum wells leads to an increase in calculated spin coherence times (T_1) compared to those of similar (100)-oriented quantum wells, exceeding 1 ns at room temperature. We have also studied the electron spin coherence times as a function of applied electric field in (100)- and (110)-oriented GaAs/AlGaAs quantum wells. T_1 is considerably more responsive to the growth-direction electric field in (110)-oriented quantum wells than in (100)-oriented quantum wells, whereas the response of T_2 is similar for both growth directions. © 2002 American Institute of Physics. [DOI: 10.1063/1.1456385]

In recent years there has been considerable interest in exploiting not only charge but also spin in solid-state electronics, which has led to new ultrafast optical studies of electron spin dynamics in bulk and quantum-well semiconductors^{1–11} and their possible application to ultrafast spin-dependent switching of electronic devices.^{12–16} One of the important factors in utilizing coherent spin dynamics in electronic devices is that the spin coherence time must be sufficiently long so that information stored in the spin polarized ensembles will not be lost during processing. Another equally important factor in spin-dependent device application is the ability to manipulate electron spin coherence.

Accurate quantitative calculations of spin coherence times are thus essential to optimizing spin coherence in quantum wells. In this work we calculate both the longitudinal spin relaxation times (T_1) and the transverse spin relaxation times (T_2) for (110)-oriented GaAs/AlGaAs quantum wells near room temperature, motivated by recent experimental investigations of long electron spin coherence times in 75-Å-GaAs/100-Å-Al_{0.4}Ga_{0.6}As quantum wells near room temperature.¹⁷ We also report the dependence of electron spin coherence times on applied electric field in (100)- and (110)-oriented GaAs/AlGaAs quantum wells near room temperature.

Electron spin coherence times in zincblende-type semiconductors near room temperature are dominated by the precessional Dyakonov–Perel (DP) mechanism,^{18–20} which is a direct result of the spin splitting of the conduction band that occurs at zero magnetic field in inversion asymmetric crystals. In quantum wells, this inversion asymmetry can arise not only from bulk inversion asymmetry of the constituent semiconductors, but also from structural inversion asymmetry of the quantum wells. The effect of bulk inversion asymmetry is dominant in structurally symmetric quantum wells. On the other hand, in asymmetric quantum wells (e.g., in the presence of compositional gradients or an external electric field along the growth direction), the contribution to electron spin decoherence due to structural inversion asymmetry may become important. In quantum wells this inversion asymme-

try can be tuned by the application of a growth-direction applied electric field; hence, the application of an electric field can be used to manipulate spin coherence times in quantum wells. The use of electric field to control spin coherence in quantum wells has also important implications to recent proposals for spin injection in semiconductors under bias.^{21,22}

To accurately describe the DP precessional spin relaxation mechanism in III–V zincblende quantum wells, we employed a nonperturbative nanostructure theory based on a generalized superlattice $\mathbf{K}\cdot\mathbf{p}$ theory solved in a fourteen-band restricted basis set.²³ Using this theory, we have previously calculated the electron spin coherence times due to bulk inversion asymmetry in zincblende semiconductor quantum wells.²⁴ Quantitative agreement between calculated spin coherence times and measurements is found for structurally symmetric quantum wells.^{8,24} In the presence of compositional gradients or an external electric field along the growth direction, this structural inversion asymmetry of the system can be naturally incorporated within the framework of envelope function theory. Further details will be available elsewhere.

When an electric field is applied along the growth direction of the quantum wells, the reflection symmetry with respect to the center of the quantum wells is broken. Consequently this structural inversion asymmetry causes an additional electron spin splitting at finite momentum, and the spin splitting gets larger as it moves away from zone center. The spin splitting due to structural inversion asymmetry is proportional to the electron momentum.²⁵ Figure 1 shows the calculated electron coherence times as a function of applied electric field along the growth direction of a 75-Å-GaAs/100-Å-Al_{0.4}Ga_{0.6}As (100)-oriented quantum wells at room temperature. Solid and dashed lines correspond to T_1 and T_2 , respectively. Here the applied magnetic field is along the growth direction.²⁴ For these calculations, we assume that the electron mobility is 800 cm²/V s and the electron density is 2.686 × 10¹⁷ cm⁻³ at room temperature. In the absence of an applied electric field, T_1 is approximately equal to half of T_2 for (100)-oriented quantum wells. This can be seen from the fact that the momentum-dependent effective magnetic field almost lies entirely in the in-plane

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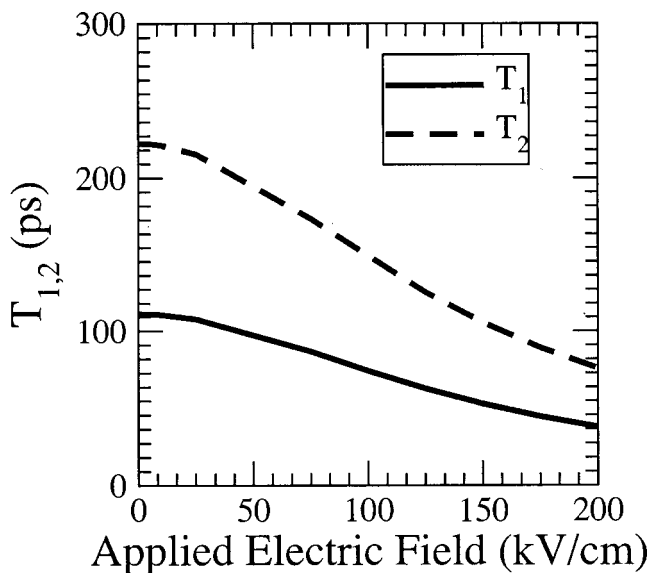


FIG. 1. Calculated electron spin coherence times as a function of applied electric field along the growth direction for (100)-oriented QWs of Ref. 10, with a solid line for T_1 and a dashed line for T_2 . The applied magnetic field is parallel to the growth direction.

direction for structurally symmetric quantum wells (see, for example, Ref. 24 for details). As shown in Fig. 1, both T_1 and T_2 have a similar dependence on applied electric field, and the dependence on applied electric field for T_1 is relatively weak compared to that in (110)-grown quantum wells (see the following discussion and Fig. 2).

Recently, Ohno *et al.* have experimentally investigated the electron spin coherence times in a series of 75-Å-GaAs/100-Å- $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ (110)-grown quantum wells near room temperature.¹⁷ The measured spin coherence times (T_1) are one order in magnitude longer than those of similar (100)-oriented quantum wells¹⁰ and exceeds 1 ns at room temperature.¹⁷ The calculated spin coherence times

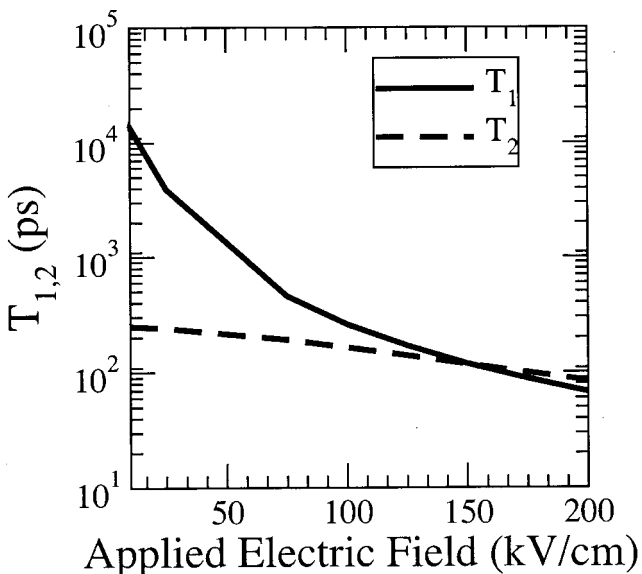


FIG. 2. Calculated electron spin coherence times as a function of applied electric field in the growth direction for (110)-oriented QWs of Ref. 17, with a solid line for T_1 and a dashed line for T_2 .

versus applied electric field in the growth direction of a 75-Å-GaAs/100-Å- $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ (110)-oriented quantum wells at room temperature are illustrated in Fig. 2. T_1 and T_2 are indicated by solid and dashed lines, respectively. To facilitate the comparison between (100)- and (110)-oriented quantum wells, we use the same electron mobility and density given above for both structures. At zero applied electric field, T_1 and T_2 in (110)-oriented quantum wells differ by a factor of 50, and T_1 has a value of ~ 20 ns at room temperature. In the absence of structural inversion asymmetry, the momentum-dependent effective magnetic field in (110)-grown quantum wells lies almost perfectly along the growth direction. It can be seen from Fig. 2 that T_1 's in (110)-oriented quantum wells are very long compared to T_2 's, and they change much more rapidly with applied electric field than T_2 's do, in particular within the range between 0 and 75 kV/cm. As shown in Fig. 2 for applied electric field greater than 150 kV/cm, T_2 exceeds T_1 . These results clearly indicate that T_1 in (110)-oriented quantum wells is very sensitive to structural inversion asymmetry whereas T_2 is much less sensitive to structural inversion asymmetry.

We found that the calculated T_1 's and T_2 's in both (100)- and (110)-oriented quantum wells with applied magnetic field in the in-plane directions are very different from those with applied magnetic field along the growth direction. Furthermore, we found that there is a strong in-plane anisotropy of electron spin decoherence in (100)-oriented quantum wells in the presence of applied electric field along the growth direction (see also Ref. 26). In contrast, the in-plane anisotropy of electron spin decoherence in (110)-oriented quantum wells is very weak.

In conclusion, we have calculated both T_1 and T_2 for (110)-grown quantum wells near room temperature. The modified symmetry of (110)-grown quantum wells leads to an increase in calculated spin coherence times (T_1) compared to those of similar (100)-grown quantum wells and exceed 1 ns at room temperature. The calculated spin coherence times for (110)-grown quantum wells are consistent with the recent experimental measurements.¹⁷ We have also examined the influence of growth-direction electric field on electron spin coherence times. It is found that T_1 is more responsive to growth-direction electric field in (110)-grown quantum wells than in (100)-grown quantum wells, whereas the response of T_2 is similar for both grown directions. These results may be used to optimize devices for the manipulation of spin coherence.

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