# Effect of nonequilibrium phonons on hot-electron spin relaxation in $n$-type GaAs quantum wells

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We have studied the effect of nonequilibrium longitudinal optical phonons on hot-electron spin relaxation in $n$-type GaAs quantum wells. The longitudinal optical phonons, due to the finite relaxation rate, are driven to nonequilibrium states by electrons under an in-plane electric field. The nonequilibrium phonons then in turn influence the electron spin relaxation properties via modifying the electron heating and drifting. The spin relaxation time is elongated due to the enhanced electron heating and thus the electron-phonon scattering in the presence of nonequilibrium phonons. The frequency of spin precession, which is roughly proportional to the electron drift velocity, can be either increased (at low electric field and/or high lattice temperature) or decreased (at high electric field and/or low lattice temperature). The nonequilibrium phonon effect is more pronounced when the electron density is high and the impurity density is low.

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## I. INTRODUCTION

Understanding spin relaxation is an important issue for the possible application of spintronic devices.[1–4] Among different kinds of spin relaxation mechanisms,[5–7] scattering plays an essential role. In general cases, phonons are assumed to form an equilibrium bath when carrier-phonon scattering is considered. This treatment works well when the carrier system is near the equilibrium. If the carriers are far away from the equilibrium (e.g., driven by an electric field or excited by a laser beam), phonons can be driven to run away from their equilibrium states significantly by carriers when the carrier energy relaxation mainly goes through the phonon emissions and the phonon relaxation time is comparable with (or longer than) the carrier-phonon scattering time. The nonequilibrium phonons in turn are able to affect the electron dynamics, including the spin relaxation. In fact, the hot-electron transport with nonequilibrium phonons has been investigated,[8–16] showing that the calculated electron energy loss rate and mobility fit better with experimental data than those obtained with the equilibrium phonons.[10,13,14] These studies also indicate that it is necessary to treat phonons as nonequilibrium ones in the hot-carrier system, and the nonequilibrium phonons may affect spin relaxation via modifying the carrier heating and drifting.

The hot-electron spin relaxation/dephasing has been studied theoretically in both (001) quantum-well structures[17–20] and bulk materials,[21] by means of the kinetic spin Bloch equation (KSBE) approach.[4] The spin relaxation/dephasing time is found to increase with electric field when both the temperature and electric field are low, especially in high mobility samples.[17–21] When the electric field is high [for which the multi-subband (in confined nanostructures)[18] and/or multi-valley[19] effect have to be taken into account], the spin relaxation/dephasing time decreases with electric field.[17–19,21] In these studies the phonons are treated as equilibrium ones. This work is to investigate the influence of nonequilibrium phonons on hot-electron spin relaxation in an $n$-type GaAs quantum well, where the spin-orbit coupling term is the Dresselhaus type[19,22] and the spin relaxation is limited by the D'yakonov-Perel' mechanism.[5]

The paper is organized as follows. In Sec. II we set up the model and the KSBEs with nonequilibrium phonons. In Sec. III the effect of nonequilibrium phonons on spin relaxation is investigated. Finally, we conclude in Sec. IV.

## II. MODEL AND KSBES

We start our investigation from an $n$-type $(001)||\hat{\mathbf{z}}$ GaAs quantum well with an in-plane electric field. The well width $a = 5$ nm. Only the lowest subband is relevant with the proper electron density $N_e$, lattice temperature $T_L$ and electric field $\mathbf{E}$. Due to the electron localization in the $\hat{\mathbf{z}}$-direction, the electron-phonon coupling is spatially inhomogeneous, i.e., the emission and absorption of phonons mainly occur in the well where electrons have substantial density. If the phonon relaxation is fast enough or the phonons [particularly, the acoustic (AC) phonons] can easily penetrate through the well interfaces, these phonons can be deemed as in equilibrium with the bulk modes. In our study we assume that the AC phonons keep in equilibrium and the longitudinal-optical (LO) phonons are nonequilibrium.[9–13,15] In order to investigate the spin relaxation of electrons which are inhomogeneously coupled with the nonequilibrium LO phonons, we combine the rate equation of the LO phonons [Eq. (2)], described as "quasi-2D",[10,13,14] with