# High-Field Resonant Magnetotransport Measurements in Small $n^+nn^+$ GaAs Structures: Evidence for Electric-Field-Induced Elastic Inter-Landau-Level Scattering

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Magnetophonon resonance at high electric fields in thin (1 to 9 $\mu$m) $n^+nn^+$ GaAs structures reveals a new mechanism of magnetoconduction, in which an electron in the $n$th Landau level can scatter *elastically* or *quasielastically* into the $(n+1)$th level.

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This Letter reports resonant magnetotransport measurements on *short* semiconductor devices, i.e., devices where contact separation is on the micron scale. By monitoring magnetophonon resonance (MPR) extrema in the transverse magnetoconductivity, $\sigma_{xx}$, of $n^+nn^+$ GaAs structures in crossed electric $(\vec{E}\parallel\vec{x})$ and magnetic $(\vec{B}\parallel\vec{z})$ fields as a function of the strength of $E$ and $B$, we have observed a new magnetotransport mechanism which is unique to the high electric fields achievable in structures of this size. In this electric-field-induced process, *(quasi)elastic inter-Landau-level scattering* (QUILLS), electrons can propagate along $\vec{E}$ by *elastic* (or *quasielastic)* transitions from the $n$th to the $(n+1)$th Landau level. The onset of the process occurs when the potential energy difference $E\,\Delta x$ across the spatial extent, $\Delta x$, of a Landau state is comparable to the cyclotron energy, $\hbar\omega_c$. This process is quite distinct from ordinary elastic inter-Landau-level processes involving a change of the electron momentum component $\hbar k_z$, parallel to $B$, which have little effect on $\sigma_{xx}$.

The devices were grown as $n^+nn^+$ layers by liquid-phase epitaxy. The $n^+$ substrate was 150 $\mu$m thick and doped to $1\times10^{18}$ cm$^{-3}$. Different active layers were grown with thicknesses of 1, 5, and 9 $\mu$m and room-temperature carrier concentrations, $n$, between $4\times10^{14}$ and $1\times10^{15}$ cm$^{-3}$. The top layer was 0.3 $\mu$m thick with $n^+=2\times10^{17}$ cm$^{-3}$. Mesas with diameters of 0.1, 0.2, 0.5, and 1.0 mm were investigated to ensure the absence of boundary effects.

The transverse magnetoresistance $R(B)$ was measured between 77 and 300 K for $B$ up to 18 T, as shown in Fig. 1, curve *a*. At high magnetic fields the applied voltage is almost entirely across the central active layer which, because of its high mobility, has a much larger magnetoresistance than the $n^+$ layers. Control measurements on structures with no active layer gave ratios $R(18\text{ T})/R(0)$ of typically 1.5 compared to values of 20 to 30 for the 1-$\mu$m active layer. MPR occurs when

$$N\hbar\omega_c = N\hbar eB_N/m^* = \hbar\omega_L, \tag{1}$$

where $N=1,2,3,\ldots,$ $m^*$ is the effective mass for the lowest conduction band, and $\hbar\omega_L$ is the longitudinal-optical phonon energy. When the resonance condition is satisfied, enhanced scattering leads to maxima[1] in $\sigma_{xx}$, as observed in $n$-GaAs[2] and other semiconductors at low electric fields ($\lesssim 100$ V/cm) with macroscopic samples (approximately millimeter scale).

 

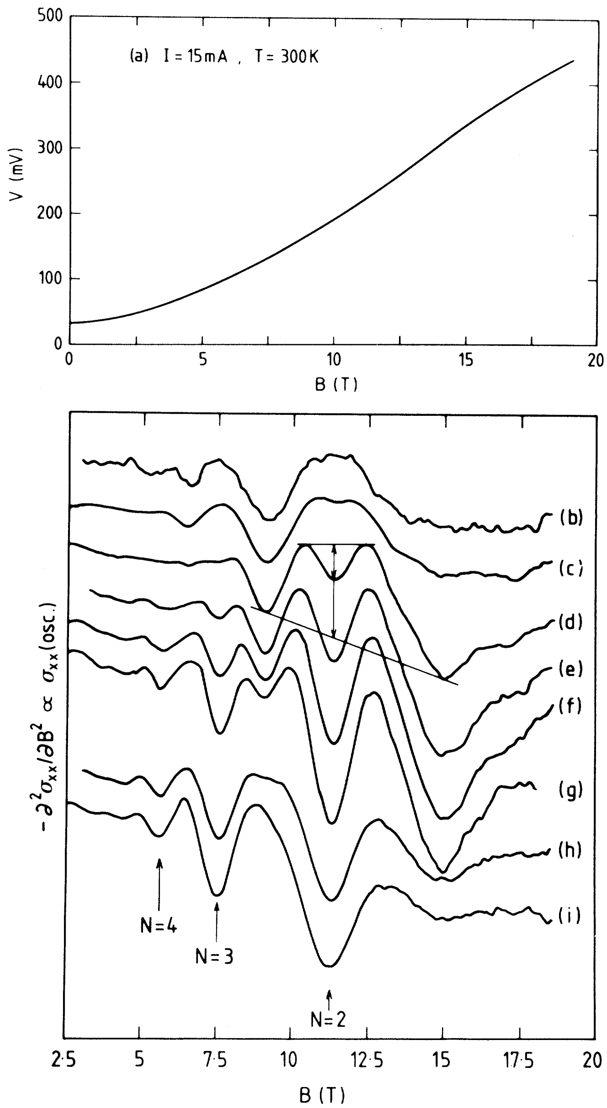


FIG. 1. Curve $a$, transverse magnetoresistance of a 1-$\mu$m-thick $n$-GaAs sandwich. Curves $b$ to $i$, transverse magnetophonon extrema of the same sample, for various values of current at 300 K. Curves $b$ to $i$ correspond to currents of 0.5, 5, 15, 20, 25, 30, 40, and 50 mA, respectively.

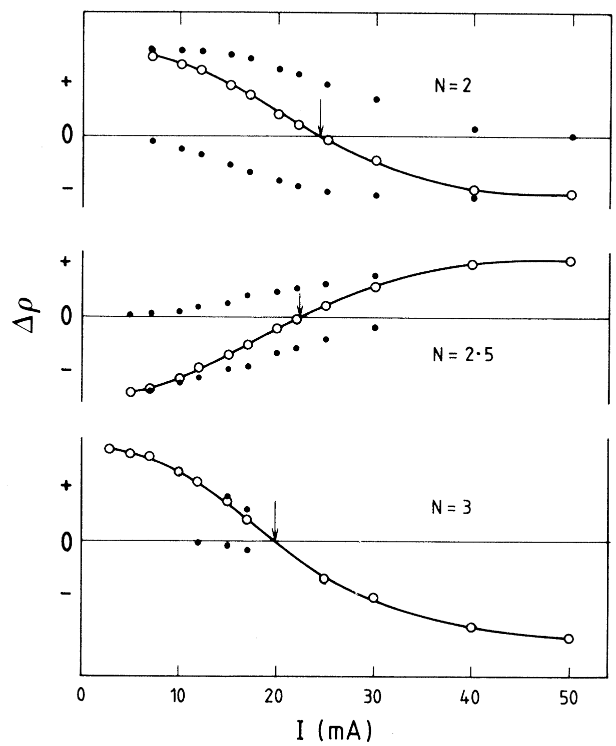


FIG. 2. The variation of the amplitudes of various MPR extrema at 300 K for increasing current (see text).

MPR extrema observed in our structures for a lattice temperature of 300 K are shown in Fig. 1, curves $b$ to $i$, for different currents. The amplitude $\Delta\sigma$ of the MPR is a few percent of the total conductivity above 10 T. Double differentiation was used to suppress the nonoscillatory magnetoresistance.[3] At low currents and low electric fields, minima in $\partial^2\sigma_{xx}/\partial B^2$ (maxima in $\sigma_{xx}$) occur at the fields $B_N$ indicated by arrows, which satisfy Eq. (1). However, as the current is increased, additional structure appears on the extrema at resonance, and at sufficiently large electric fields, minima rather than maxima occur in $\sigma_{xx}$ at resonance. To locate the transition from maxima to minima in $\sigma_{xx}$, we plot the variation of the amplitude of each resonant ($N$) and off-resonant ($N+\frac{1}{2}$) extremum versus current, as shown in Fig. 2. Because of the limitation of the maximum magnetic field available, analysis of the structure between $N=1$ and 2 is difficult and has not been plotted. At currents where a weak minimum is superimposed on a stronger maximum, amplitudes of both these mimina and maxima (defined as shown in curve $d$ of Fig. 1) are recorded and their amplitude difference is taken as the *effective amplitude* of the resonance. The critical currents $I_c$ at which maxima convert into minima, i.e., where the *effective amplitude* is zero, are indicated by arrows. From the undifferentiated magnetoresistance, the corresponding values of electric field $E_c(N)$ are deduced. The values of $E_c(N)$ increase with decreasing $N$. The straight-line dependence shows that they fit the relation

$$E_c(N) \propto 2N^{-3/2}[(N+\tfrac{1}{2})^{1/2}+(N+\tfrac{3}{2})^{1/2}]^{-1},$$

which is derived below from the properties of the electron eigenfunctions.

The Hamiltonian for the cross-field problem is

$$\mathscr{H} = (1/2m^*)(\vec{p} + e\vec{A})^2 + exE,$$

with $\vec{A} = B(0,x,0)$. Spin effects are neglected since spin-flip MPR in GaAs has not been observed. The eigenfunctions and energy eigenvalues are given by

$$\psi_n = \exp(ik_y y)\exp(ik_z z)\phi_n(x - x_0)$$

and

$$\epsilon_n = (n + \tfrac{1}{2})\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m^*} + eEx_0 + \frac{e^2E^2}{2m^*\omega_c^2},$$

where $\phi_n$ are simple harmonic-oscillator-like solutions, $n = 0, 1, 2, 3, \ldots$, and $k_y = 0, \pm 2\pi/L, \pm 4\pi/L, \ldots$. The center coordinate $x_0$ is given by

$$-x_0 = \hbar k_y/m^*\omega_c + eE/m^*\omega_c^2, \qquad (2)$$

and $L$ is the length along the $y$ axis. The energy eigenvalues are plotted schematically for a particular value of $k_z$ in Fig. 3. It is worth noting here that although scattering processes involving a change of $k_z$ have a crucial effect on the longitudinal magnetoconductivity $\sigma_{zz}$, they have little effect on $\sigma_{xx}$. At low electric fields, eigenfunctions ($\alpha$ and $\beta$ in Fig. 3) of the same energy in adjacent Landau levels have a very small spatial overlap, and the elastic scattering rate between levels is low. However, at a large enough field, $E_c$, the eigenfunctions in adjacent Landau levels which are now at the same energy ($\alpha$ and $\gamma$) have a more significant spatial overlap. Hence, at $E_c$, elastic or quasielastic scattering between the Landau levels (QUILLS) becomes appreciable. This scattering can be either by ionized impurities (elastic) or by acoustic phonons (quasielastic).[4] QUILLS introduces a contribution to $\sigma_{xx}$ not available at low electric fields. Since the $\phi_n$ have exponential tails, this new contribution should increase rapidly for small increments of $E$ around $E_c$. The change of sign of the MPR extrema at large $E$ can now be understood in terms of the effect on $\sigma_{xx}$ of competition between two types of scattering processes. At resonance the electron gas is cooled by LO phonon emission. This transfers electrons from spatially extended high-energy (high-$n$) states into less extended low-energy states. QUILLS, which relies on spatial superposition of the eigenfunctions, therefore decreases at resonance and makes a smaller contribution to $\sigma_{xx}$ than at off-resonance magnetic fields. When the decrease in contribution to $\sigma_{xx}$ produced by QUILLS exceeds the increase due to scattering by resonant MPR emission, minima rather than maxima in $\sigma_{xx}$ at resonance should occur. At the half-integer

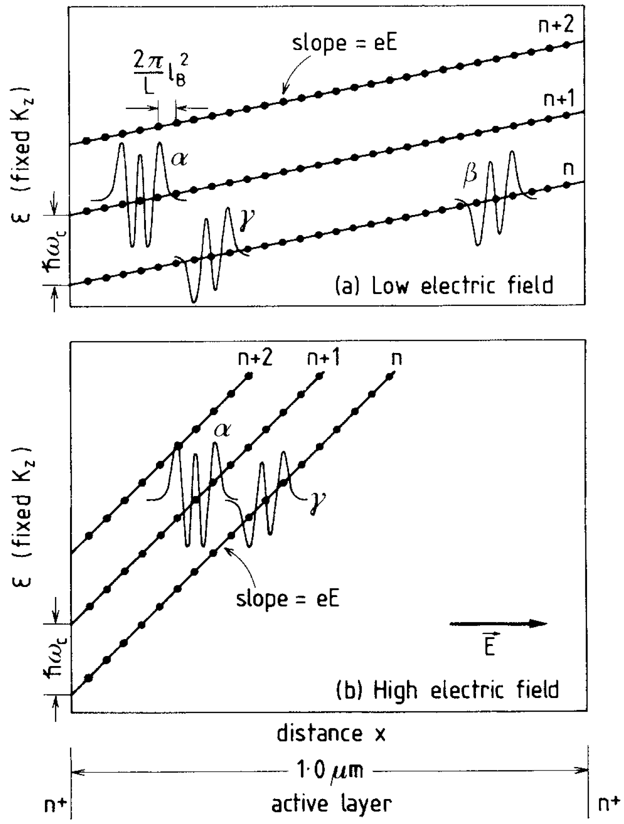


FIG. 3. Schematic plot of the energy eigenvalues of various Landau levels ($n$) for fixed $k_z$ (a) for low electric fields and (b) at an electric field large enough to give a significant probability of scattering between two eigenfunctions of states in the $n$th and $(n+1)$th Landau levels of the same energy. The closed circles on the solid line represent the quantized values, $x_0$. The $\phi_n(x - x_0)$ are sketched for $n = 3$ and 4.

values of $N$, resonant magnetophonon processes do not contribute to $\sigma_{xx}$ and to the cooling of the electron gas. Therefore, at these values of $B$, QUILLS is especially effective in increasing $\sigma_{xx}$ and leads to maxima in it at large $E$.

Since the slope of the lines in Fig. 3 is $eE$, the onset condition of QUILLS is

$$eE_c(\Delta x_n + \Delta x_{n+1})/2 = \hbar\omega_c, \qquad (3)$$

where $\Delta x_n$ is the spatial extent of $\phi_n$. The $\Delta x_n$ are given by the classical limits of the simple harmonic motion, $\Delta x_n = 2(2n+1)^{1/2} l_B$, where $l_B = (\hbar/eB)^{1/2}$. Since the electron distribution function decreases rapidly at an LO phonon energy above the band edge,[1] the main contribution to the $N$th magnetophonon resonance involves transitions from the $n = N$ to $n = 0$ Landau level. Substitution of the resonance condition (1) into Eq. (3) gives the criti-

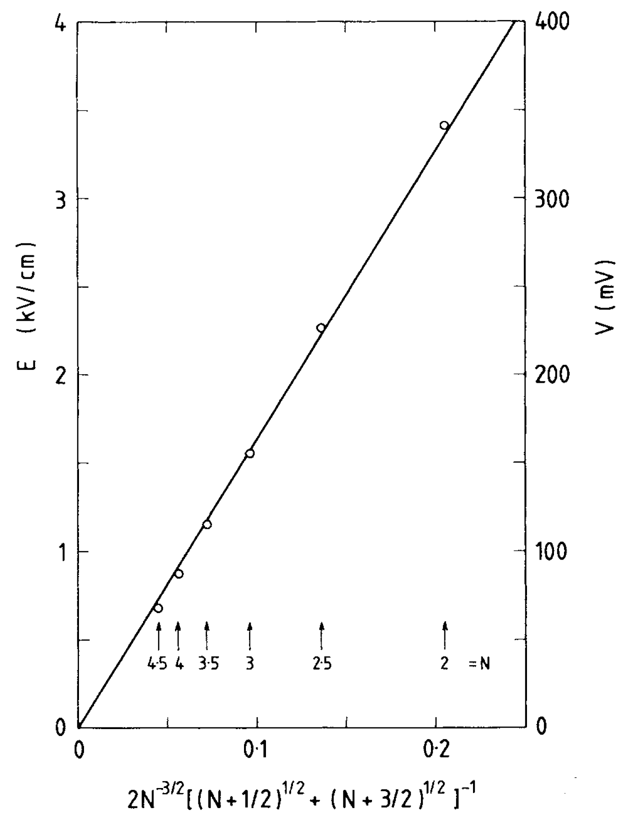


FIG. 4. The critical electric field (at which the signs of the MPR extrema change) plotted against $2N^{-3/2}[(N+\frac{1}{2})^{1/2}+(N+\frac{3}{2})^{1/2}]^{-1}$. The solid curve is the best straight-line fit through the origin. The data points are taken from the intercepts in Fig. 2 for a 1-$\mu$m sample.

cal condition for electrons in the $N$th Landau level:

$$eE_c=(\hbar m^*)^{1/2}(\omega_L/2)^{3/2}2N^{-3/2}\times[(N+\tfrac{1}{2})^{1/2}+(N+\tfrac{3}{2})^{1/2}]^{-1}. \quad (4)$$

Since Eq. (4) contains either physical constants ($h$ and $e$) or known properties of GaAs ($m^*$ and $\omega_L$), a quantitative comparison can be made between the model and the measured values of critical electric field. We find that the slope given by the data points in Fig. 4 is 30% smaller than that calculated from Eq. (4). The precise condition for crossover from maximum to minimum in $\sigma_{xx}$ at resonance is critically dependent on the relative strengths of the contributions of QUILLS and magnetophonon processes. The agreement is quite good considering that our method of obtaining $I_c$ and hence $E_c$ is somewhat empirical and that there is an estimated 20% uncertainty in the effective active-layer thickness and hence in $E$. A more detailed analysis of the $E$ dependence of the resonances, which requires details of the electron distribution function and the scattering rate for QUILLS, is in progress.

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[3]R. A. Stradling and R. A. Wood, J. Phys. C **3**, 2425 (1970). Since the mesa diameter is much greater than its thickness, the Hall electric field component is effectively shorted out by the conducting $n^+$ outer layers. Therefore, $J_x=\sigma_{xx}E_x$ and $R(B)$ is proportional to $E_x/J_x=1/\sigma_{xx}$. The large diameter also makes the contribution of the "Hall" current $J_y$ negligible. Since the resonant structure in $\sigma_{xx}$ is weak, $\partial^2R/\partial B^2$ gives the oscillatory part of $\sigma_{xx}$, with maxima in $\sigma_{xx}$ corresponding to minima in $R$.

[4]Since $\Delta x_0 \sim l_B$, Eq. (2) gives $-\Delta k_y=(1/l_B^2)\Delta x_0 \sim 1/l_B$, where $l_B \sim 100$ Å at 10 T. This relatively large change in $k_y$ is presumably more effectively supplied by acoustic phonons than by ionized impurity scattering. Interestingly, although $k_y$ changes in the scattering process, the group velocity component $v_y$ is not relaxed. Since $m^*v_y=p_y+eA_y=p_y+eBx$, in a scattering process, $m^*\Delta v_y=\hbar\Delta k_y+eB\Delta x_0=0$.