# Direct observation of tunneling between Landau levels in barrier-separated two-dimensional electron-gas systems

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We have investigated the tunneling processes between two systems of independently contacted quantized states. Shifting the two systems energetically with respect to each other, we were able to observe transitions between different subbands on both sides of the barrier as a series of peaks in the derivative of the tunneling current $dI/dV$. If a magnetic field is applied perpendicular to the sample, additional peaks are resolved in $dI/dV$. These peaks are unambiguously identified as tunneling processes between different Landau levels on both sides of the barrier.

Tunneling into Landau levels became interesting since Tsui and collaborators[1–4] had investigated the Landau-level structure in an accumulation layer on InAs-oxide-Pb junctions by tunneling spectroscopy. Similar experiments were carried out on PbTe-oxide-Pb and $In_xGa_{1-x}As$-oxide-Pb junctions.[5,6] Presently, magnetotunneling experiments are mainly performed on high-quality, single-barrier heterostructures. Hickmott[7] had investigated $n^-$-GaAs–$Ga_{1-x}Al_xAs$–$n^+$-type GaAs structures when a magnetic field is applied parallel to the junction. On these samples, tunneling into bulk Landau levels was evident as field-dependent oscillations in the (first) derivative of the tunneling current, $dI/dV$. Snell *et al.*[8] and Chan *et al.*[9] were able to observe magneto-tunneling effects on $n^-$-type GaAs-InP–$n^+$-type $In_xGa_{1-x}As$ barrier structures. Oscillations in $d^2I/dB^2$ were interpreted by a tunneling process into interfacial Landau states in the $n^+$-type $In_xGa_{1-x}As$. On double barriers, Mendez[10] has observed resonant tunneling of electrons through Landau levels inside the well. Goldman[11] showed both experimentally and theoretically that a space-charge buildup inside of the double barrier strongly influences the tunneling current. Most recently, Leadbeater,[12] Eaves,[13] and co-workers have published results about tunneling through $In_xGa_{1-x}As$-InP double barriers, applying a magnetic field both perpendicular and parallel to the junction. A transverse magnetic field significantly changed the *I-V* characteristics and eliminated the negative differential resistance for high magnetic fields.

We have investigated magneto-oscillations in the tunneling current between an accumulation layer and an inversion layer. Although only separated by a barrier of 200 Å, independent contacts to both two-dimensional electron-gas systems were achieved. Thus, for the first time we have a system where the subbands and Landau levels on each side of the barrier can be shifted energetically with respect to each other. Applying a voltage $V_g$ to the junction, all transitions between the quantized states on both sides of the barrier are reflected in the tunneling current directly, while the energy of the observed transitions is $eV_g$. It should be pointed out that the presented system is capable of a large number of fundamental experiments which have not been possible before. For example, impurities in the barrier and the density of states in the two-dimensional electron gas can easily be investigated. In principle, subband and Landau-level inversion can also be achieved.

The samples consist of an unintentionally *p*-type doped GaAs layer grown on a semi-insulating substrate ($N_A < 1\times10^{15}$ cm$^{-3}$), followed by an undoped spacer ($d = 50$ Å), doped $Ga_{1-x}Al_xAs$ ($d = 45$ Å, $N_D = 4\times10^{18}$ cm$^{-3}$), another spacer ($d = 100$ Å) and *n*-type-doped GaAs ($d = 800$ Å, $N_D = 1.2\times10^{15}$ cm$^{-3}$). An additional GaAs cap layer was highly *n*-type doped ($d = 150$ Å, $N_D = 6.4\times10^{18}$ cm$^{-3}$). The resulting band structure is shown in Fig. 1(a). The electron concentration in the inversion layer, $n_s = 4.2\times10^{11}$ cm$^{-2}$, and the accumulation layer $n_s' = 2.6\times10^{11}$ cm$^{-2}$ was determined from the two periods observed in the Shubnikov–de Haas oscillations when both channels were contacted simultaneously.

Figure 1(b) schematically shows the sample geometry. The contacts to the inversion layer were formed using a Au-Ge alloy ([Au]:[Ge]=8:1). For an Ohmic contact to the accumulation layer Au-Ge was used also, but in this case the Au-Ge was only slightly diffused into the highly doped GaAs by a shallow diffusion process. Beside the top contact the *n*-type doped GaAs layers were removed selectively. All current-voltage (*I-V*) and $dI/dV$ measurements were made using a four-terminal conductance bridge[14] with a modulation frequency of 39 Hz and a modulation voltage of 0.3 mV to achieve a high resolution. All series resistances, even the magnetic-field-dependent resistance $R_{2D\,EG}$, are compensated by the four-terminal technique. It is important to note that although the series resistances are compensated, the measurements are still disturbed by the occurrence of a Hall voltage $V_H$ parallel to the gate [see Fig. 1(b)]. At con-

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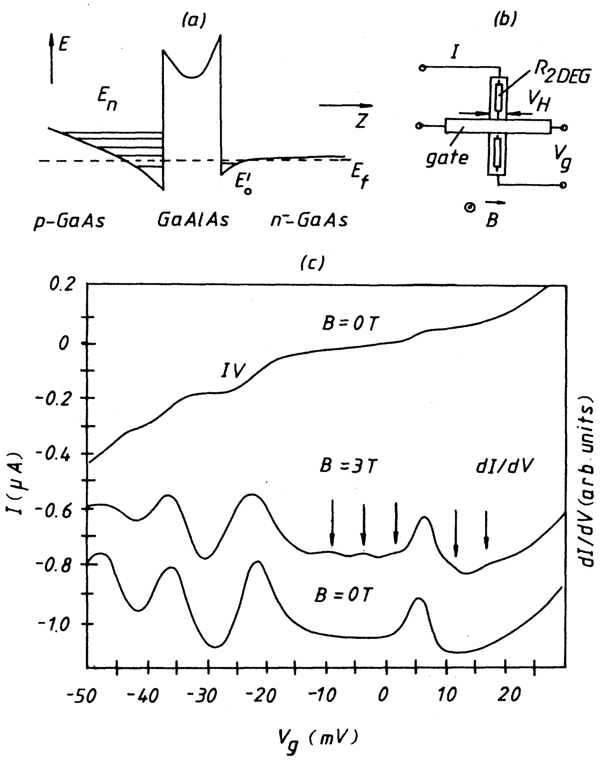


FIG. 1. (a) Band structure of typical samples. $E_n$ and $E_0'$ are the subbands in the inversion layer and the accumulation layer, $E_F$ is the Fermi level. (b) Schematic figure of the sample geometry. $I$ is the tunneling current and $V_g$ the corresponding gate voltage. $R_{2D\,EG}$ represents the series resistance in the inversion layer and $V_H$ is the Hall voltage at the gate contact. (c) $I$-$V$ and $dI/dV$ curves for one typical sample (No. 1816/13). The magnetic-field-induced structure in $dI/dV$ is indicated by arrows.

stant magnetic field and constant applied voltage, $V_H$ depends on the current in the inversion layer. As this current is directly proportional to the width of the 2D channel, the parasitic influence of $V_H$ can be reduced by reducing the dimensions of the sample.

Figure 1(c) shows the $I$-$V$ characteristics and its derivative for one typical sample (No. 1816/13). From Shubnikov–de Haas measurements it is known that only the lowest subband, $E_0$, is occupied in the inversion layer. We have demonstrated in a previous paper[15] that steps in the $I$-$V$ characteristics occur each time, when electrons are tunneling from one subband through a barrier into another subband. Therefore, we contribute the step in $I$-$V$ and the corresponding peak in $dI/dV$ at $V_g=+6$ mV (inversion layer grounded) to a tunneling process from $E_0$ into the lowest subband in the accumulation layer, $E_0'$. As this is the only structure in forward bias, we conclude that only one subband exists in the accumulation layer, which is shown in Fig. 1(a). From the electron concentration $n_s$ the Fermi level $E_F$ is calculated to be 15 meV above $E_0$. Using the value of $(E_0'-E_0)=6$ meV and the fact that without applied voltage $E_F$ is constant through the sample $E_F$ is easily determined to be 9 meV above $E_0'$. From this, one can evaluate $n_s'=2.6\times10^{11}$ cm$^{-2}$, which agrees well with the value obtained from the Shubnikov–de Haas measurements. The first step in $I$-$V$ in reverse bias (peak in $dI/dV$) is due to a tunneling process from $E_0'$ into the first subband in the inversion layer, $E_1$, and the following peaks in $dI/dV$ are due to tunneling processes into the higher subbands. Up to eight subbands were observed.

If a magnetic field $B$ is applied perpendicular to the sample additional structure is revealed in $dI/dV$. Figure 1(c) shows the $dI/dV$ characteristics for $B=3$ T, where the additional peaks are indicated by arrows. In Fig. 2(a) some selected $dI/dV$ curves are plotted at different magnetic field. It is apparent that these additional peaks are shifted to higher voltages, while the peak distances and the peak amplitudes increase. The peaks vanish if they approach the subband resonance position. Figure 2(b) shows a fan chart of the magnetic-field-induced peak positions. All observed peak positions depend linearly on $B$, whereas the peaks stay equidistant. It is demonstrated below that our experimental results can be explained by tunneling processes between different Landau levels on both sides of the barrier.

Earlier experiments[1–6] were always carried out on samples where electrons tunnel from Landau levels of an accumulation layer into a metal or a highly $n$-type doped electrode. Because of the high electron scattering rates, Landau levels do not exist on the highly doped or metal of the junctions and the tunneling electrons have an arbitrary wave vector between 0 and the Fermi wave vector $k_F$ parallel to the barrier. If the Fermi level is aligned to the Landau levels in the accumulation layer, a series of oscillations is observed in $d^2I/dV^2$ for the Landau levels of each electronic subband.[2] Most recently, Kane *et al.*[16] found evidence of inter-Landau-level tunneling in a two-dimensional electron gas between regions of different electron densities, which were induced by a gate contact. If a magnetic field was applied, the current between the two regions showed a backward $p$-$n$-diode-like behavior. Treating the Landau levels at the boundary of these re-

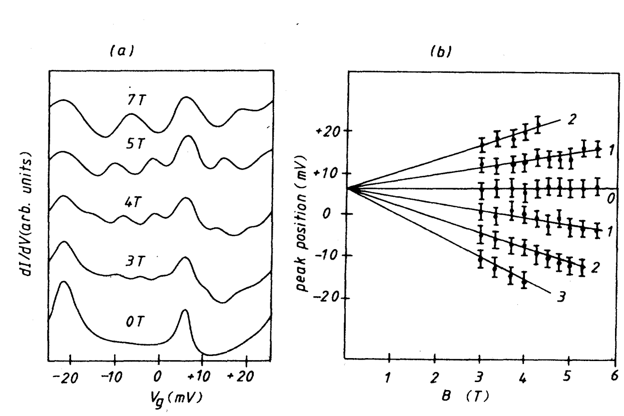


FIG. 2. Selected $dI/dV$ curves for different magnetic fields (a). The field-induced peaks are clearly resolved. (b) Fan chart of the observed peak positions vs magnetic field. The numbers at the end of the lines denote the change of the Landau-level index $\Delta l$.

gions in analogy to a *p-n* junction, the existence of inter-Landau-level tunneling was deduced.

In our samples, however, subbands and Landau levels exist on both sides of the barrier and can be shifted energetically with respect to each other. If scattering processes can be neglected, $k_\parallel$ is conserved and only tunneling processes between Landau levels of the same index should be possible. Note that if $E_0'$ in the accumulation layer matches a subband in the inversion layer, the Landau levels are aligned automatically. This means that there should be no additional structure in $dI/dV$ besides the subband resonance positions, because there is no coupling between $k_\parallel$ and $k_\perp$ of the tunneling electrons.

However, a coupling between $k_\parallel$ and $k_\perp$ can be induced by a scattering processes, as for example impurity scattering inside the barrier. In this case a part of $k_\perp$ of the incoming electron can be converted into parallel momentum, and therefore additional structure in $dI/dV$ due to Landau-level–Landau-level tunneling (LLT) is expected.

One can see from the fan chart in Fig. 2(b) that the observed additional peaks in $dI/dV$ show a linear behavior with the magnetic field. This rules out that the observed peaks have their origin in magnetoresistance oscillations of the inversion layer, because such oscillations are periodic in $1/B$. As the peak distances are equal to $\hbar\omega_c/e$, we conclude that the peaks in $dI/dV$ correspond to tunneling processes between different Landau levels on both sides of the barrier. If the effective mass is calculated from the peak distances, one gets $m^*/m = 0.066 \pm 0.005$. Due to the experimental error in the present experiment, we were not able to detect any influence of nonparabolicity effects. Note that the good agreement of measured effective mass with the literature values is proof of the fact that there is practically no voltage drop in the *n*-type GaAs layer, and that the energy levels in the accumulation layer are really shifted by $eV_g$ with respect to the inversion layer.

From the slope of the lines plotted in Fig. 2(b) it can be concluded that the Landau-level index of the tunneling electrons is changed by $\Delta l$ with $\Delta l = 1$, 2, 3. For decreasing magnetic fields, the Landau-level splitting and the zero-point energy decreases. As at low voltages, tunneling will only occur between the Landau levels of $E_0$ and $E_0'$, the first LLT peak in $dI/dV$ is moved towards the $E_0 - E_0'$ resonance position with decreasing magnetic field. The extrapolation for $B = 0$ T in fact yields the experimentally observed resonance position at $V_g = 6$ mV. Figures 3(a)–3(c) schematically show the observed LLT processes at $B = 3$ T for $\Delta l = 1, 2, 3$ in reverse bias. From the electron concentrations in the two 2D channels the filling factors were calculated neglecting all spin effects. This is indicated by the thick bars in Fig. 3. For the bias voltages used in our experiments, one can assume that both $n_s$ and $n_s'$ are approximately constant and that the filling factors do not change significantly with $V_g$. If the energy of the incoming electrons is increased by $eV_g = 1\hbar\omega_c$ ($\Delta l = 1$), tunneling can occur between the first Landau level in the accumulation layer, LL1′, and the second Landau level in the inversion layer, LL2 [Fig. 3(a)]. Tunneling between LL0′ and LL1 is not possible as

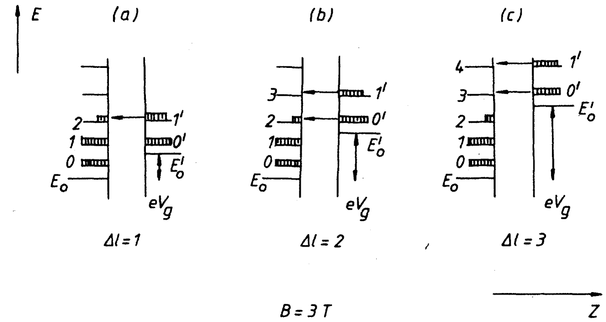


FIG. 3. The arrows indicate the possible tunneling processes between Landau levels of $E_0$ and $E_0'$ at $B = 3$ T. Tunneling between two completely filled Landau levels is not possible. The numbers indicate the Landau-level indices, $V_g$ is the applied voltage, and $\Delta l$ is the change of the Landau-level index of the tunneling electron.

as LL1 is fully occupied. If $eV_g = 2\hbar\omega_c$ ($\Delta l = 2$), LL0′-LL2 and LL1′-LL3 tunneling processes can occur, which is shown in Fig. 3(b). The situation for $\Delta l = 3$ is shown in Fig. 3(c). Higher or lower magnetic fields only change the filling factors of the Landau levels. At $B = 7$ T, for example, the accumulation layer is in the quantum limit and two Landau levels are occupied in the inversion layer. If a positive voltage is applied to the junction, electrons tunnel from the inversion layer into the accumulation layer. As Landau levels exist on both sides of the $Ga_{1-x}Al_xAs$ barrier, LLT peaks can also be observed.

In the present experiment, we only have observed LLT between the Landau levels of the lowest subbands $E_0$ and $E_0'$. In forward bias, we observe two LLT peaks. This is due to the fact that $E_0'$ is close to the conduction-band edge in the bulk GaAs. In reverse bias, the LLT peaks of the higher subbands are probably washed out by the overlapping subband-subband resonances ($\Delta l = 0$). This is explained by the fact that the energy differences between the higher subbands are considerably smaller than $E_1 - E_0$. In addition, the linewidths of the observed transitions increase with increasing magnetic field. This can be explained classically by the increasing length of the particle trajectory in the $Ga_{1-x}Al_xAs$. Therefore, the scattering probability in the barrier is increased for increasing magnetic field, which results in a broadening of the $k_\perp$ distribution of the tunneling electrons. In fact, this may be the reason why the amplitude of observed LLT peaks is quite large at high magnetic fields.

As can be seen from Fig. 2, the amplitude of the LLT peaks at high magnetic field is comparable to the subband resonances. Thus, our system is capable of obtaining Landau-level inversion. If the electrons in the accumulation layer are in the quantum limit, it is possible to inject electrons into a Landau level of the inversion layer, where empty Landau levels exist below the injection energy. This process is a promising mechanism to obtain a tunable source for far-infrared emission.

In summary, we have investigated the tunneling processes between two barrier-separated two-dimensional electron-gas systems, which can be shifted energetically with respect to each other. Up to eight subbands were observed in the inversion layer using tunneling spectroscopy. If a magnetic field is applied perpendicular to the sample, Landau levels are created on both sides of the barrier. These Landau levels are observed as two periods in the Shubnikov–de Haas oscillations and as additional peaks in the derivative of the tunneling current. It is demonstrated that normally forbidden transitions between different Landau levels are enabled by breaking the $k_{\parallel}$ conservation through scattering processes in the $Ga_{1-x}Al_xAs$ barrier. With the present system, Landau-level inversion and tunable far-infrared radiation can be achieved.

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