Momentum Conservation in Tunneling Processes between Barrier-Separated 2D-Electron-Gas Systems

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We directly determine the momentum conservation rules for tunneling processes between two independently contacted two-dimensional-electron-gas systems on GaAs-GaAlAs heterostructures. In transverse magnetic fields, the conservation of the canonical momentum results in a new and giant broadening of the subband resonances. As a consequence, the mean values of the wave functions, even for nonoccupied subbands, can be determined directly.

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Tunneling processes in transverse magnetic fields became a topic of increased interest in the last few years. In double-barrier heterostructures, it was found that the position of the negative differential resistance is shifted if a magnetic field is applied parallel to the plane of the barriers.[1] Further, the tunneling current is reduced by an increased effective barrier height.[2,3] Magnetoquantized interface states, corresponding to classical skipping orbits, were investigated on both InP-InGaAs (Refs. 4 and 5) and GaAs-AlGaAs (Ref. 6) single-barrier heterostructures. Resonant tunneling into so-called cycloidal interface states is also evident at high magnetic fields.[7,8] At extremely high fields, an anticrossing of the energy levels on both sides of a tunneling barrier occurs, which is apparent as a new series of resonances in the tunneling current.[9-11] As an additional feature, the negative differential conductivity region in the current-voltage characteristics of double-barrier structures is washed out.[12] Basic calculations about tunneling in transverse magnetic fields[13-16] and hybrid magnetoelectric quantized states[17,18] were also performed, since in narrow-gap semiconductors these states offer interesting possibilities for tunable light sources and far-infrared detectors.

In order to investigate the momentum conservation rules, we have studied the tunneling processes between two independently contacted two-dimensional-electron-gas systems, separated by a barrier of 200 Å. Applying a bias voltage V_b across the barrier, the quantized states on both sides of the barrier are shifted energetically by eV_b with respect to each other. All transitions between quantized states are reflected in the tunneling current directly.[19] In transverse magnetic fields, we observe a tremendous splitting of the subband resonances, being more than 1 order of magnitude larger than the cyclotron energy $\hbar\omega_c$. This confirms that Landau levels are not involved in this effect.

The samples consist of an unintentionally p-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 GaAlAs ($d=45$ Å, $N_D=4\times10^{18}$ cm^{-3}), another spacer ($d=100$ Å), and n-doped GaAs ($d=800$ Å, $N_D=1.2\times10^{15}$ cm^{-3}). An additional GaAs cap layer was highly n-doped ($d=150$ Å, $N_D=6.4\times10^{18}$ cm^{-3}). The resulting band structure is shown in Fig. 1. Thus, we have a system where an accumulation layer and an inversion layer are separated by a barrier of only 200 Å. From Shubnikov–de Haas measurements it was deduced that only one subband is occupied in both the inversion layer and the accumulation layer, having an electron concentration of $n_s^{\text{inv}}=6.1\times10^{11}$ cm^{-2} and $n_s^{\text{acc}}=5.8\times10^{11}$ cm^{-2}, respectively. The contacts to the inversion layer were found using a AuGe alloy. For an Ohmic contact to the upper channel AuGe was used also, but in this case the AuGe was only slightly diffused into the n-doped GaAs. The GaAs layer around the top contact were removed selectively, yielding independent contacts to both electron-gas systems. All measurements of the current-voltage (I-V) characteristics and its derivative (dI/dV) were made using a four-terminal conductance bridge[20] with a modulation frequency of 22 Hz and a modulation voltage of 0.3 mV to achieve a high

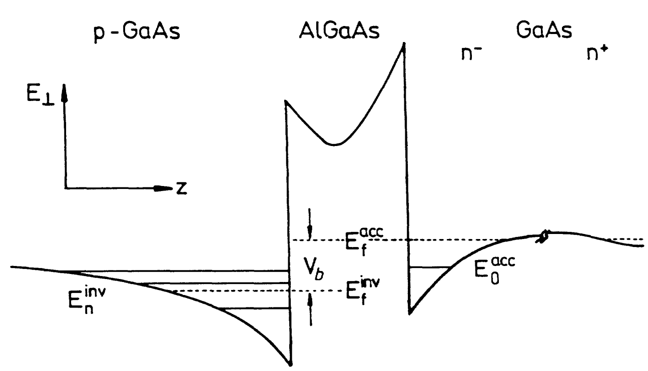

FIG. 1. Band structure of a typical sample. E_0^{acc} and E_n^{inv} denote the subbands in the accumulation and inversion layers. E_f^{acc} and E_f^{inv} are the corresponding Fermi levels.

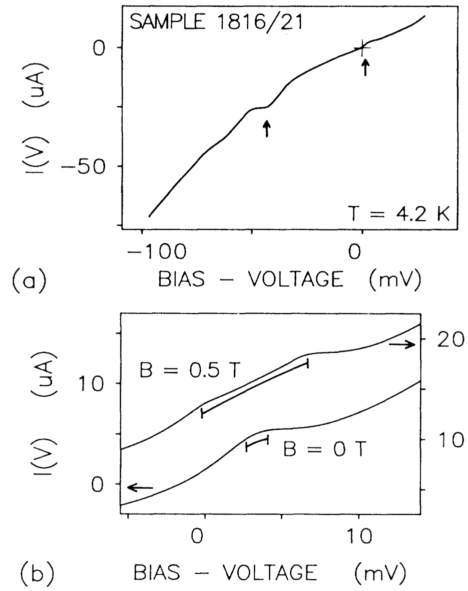

FIG. 2. (a) I-V-characteristics of sample 1816/21 at $B=0$ T. The resonance positions are marked by arrows. (b) Resonance broadening in transverse magnetic fields, schematically shown. The widths of the resonances are indicated by the bars.

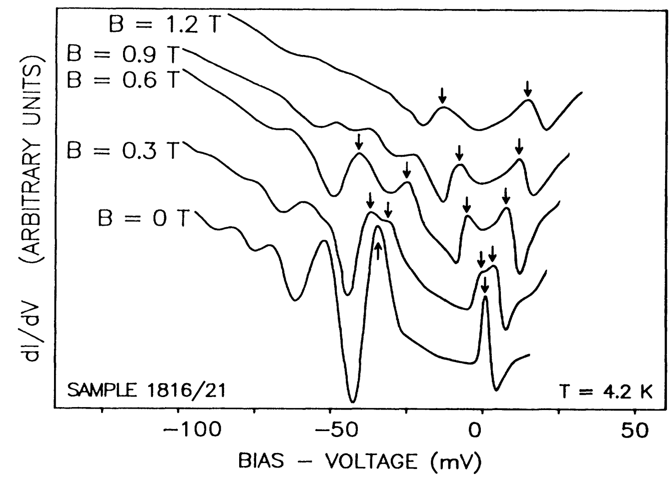

FIG. 3. dI/dV curves of sample 1816/21 for various transverse magnetic fields. The arrows indicate the splitting of the $B=0$-T resonance peaks.

resolution.

Figure 2(a) shows the I-V characteristics of sample 1816/21. Several steplike structures are clearly observed, which are washed out more negative bias voltages. If a transverse magnetic field is applied to the sample, the current resonances broaden drastically, as shown in Fig. 2(b). This effect is much better resolved in dI/dV, where the broadening of the current resonances results in a splitting of the $B=0$-T dI/dV peaks (Fig. 3). With increasing magnetic field, the peaks in dI/dV are broadened and the tunneling current decreases considerably.

We first discuss in detail the $B=0$-T results: The total energy of an electron in a two-dimensional system can be written as $E=E_\perp+E_\parallel$, where $E_\perp$ is the subband energy and $E_\parallel=\hbar^2k_y^2/2m^*+\hbar^2k_x^2/2m^*$. If the momentum of the electrons parallel to the barrier is conserved during the tunneling process, resonances between the two quantized systems will occur, if two states are aligned energetically in $E_\perp$. $E_\parallel$ will have no influence on the tunneling current. This situation is achieved each time a subband in the accumulation layer matches a subband in the inversion layer. In this case resonances appear in the tunneling current, which are better resolved as sharp peaks in the dI/dV curves (Fig. 3) due to the well defined $E_\perp$ distribution in the emitter electrode. Thus, we attribute the peak at $V_b=+2$ mV (inversion layer grounded) to a tunneling process from E_0^{inv} into the lowest subband in the accumulation layer, E_0^{acc}. As only one peak in dI/dV is observed in forward bias, we conclude that only one subband exists in the accumulation layer. At negative bias, the first peak in dI/dV is due to a tunneling process from E_0^{acc} into the first subband in the inversion layer, E_1^{inv}. The subsequent peaks in dI/dV are due to tunneling processes into the higher subbands. If the parallel momentum were not conserved, the $E_\perp$ distribution of the incident electrons would have a width comparable to the Fermi energy, resulting in broad structures in dI/dV. From the experimental data in Fig. 3, however, we get a value of 8 meV for the linewidth in $e\,dI/dV$ of the E_0^{acc}-E_1^{inv} transition. This is much smaller than the Fermi energy $E_F^{\text{acc}}=21$ meV, which indicates that the $k_\parallel$ conservation is a valid assumption at $B=0$ T.

In order to gain more information about the momentum conservation rules, a transverse magnetic field is applied to the sample. Classically, the Lorentz force couples the components of momentum in the y and z directions, which quantum mechanically is nothing less than the conservation of the canonical momentum. For an electron traveling through the barrier in the z direction, the wave vector in the y direction is changed by $\Delta k_y=eBd/\hbar$, where d is the distance traveled. This results in a change of k_z by Δk_z, corresponding to a change in $E_\perp$ by $\Delta E_\perp$. In terms of the total energy, the incident electron is described by $E_\perp+\hbar^2k_y^2/2m^*+\hbar^2k_x^2/2m^*$. Beyond the barrier, the total energy is conserved and can be written as

$$(E_\perp+\Delta E_\perp)+(k_y+\Delta k_y)^2\hbar^2/2m^*+\hbar^2k_x^2/2m^* .$$

Therefore, $\Delta E_\perp$ is evaluated as

$$\Delta E_\perp=(-2k_y\Delta k_y-\Delta k_y^2)\hbar^2/2m^* . \tag{1}$$

Since the wave functions and subband energies in the 2D systems are only weakly influenced by the occurrence of magnetoelectric hybrid states,[4-7,9,17,18] at low magnetic fields, the zero-field resonance condition $E_0^{\rm acc}=E_n^{\rm inv}$ can be replaced by

$$E_n^{\rm inv}=E_0^{\rm acc}+\Delta E_\perp . \tag{2}$$

This means, that the resonance condition for a tunneling electron is shifted by $\Delta E_\perp$. Consequently, resonant tunneling now occurs at a bias voltage $V_b+\Delta V_b$, where $\Delta V_b=\Delta E_\perp/e$. From Eq. (1) it is obvious that $\Delta E_\perp$ is a function of the magnetic field, the length of the trajectory, and the value of k_y of the tunneling electrons. Note that the sign of $\Delta E_\perp$ depends on the sign of k_y. If $\Delta E_\perp$ is positive, a tunneling electron will gain k_z and lose k_y, which means that for this electron, a resonant tunneling process is possible at lower gate voltages than in the case of zero magnetic fields. For negative values of $\Delta E_\perp$ resonant tunneling processes into the nth subband of the inversion layer can still occur at energies $E_0^{\rm acc}\geq E_n^{\rm inv}$.

Since the electrons in the emitter electrode have k_y values limited by $\pm k_F$, the range of the corresponding $\Delta E_\perp$ values is thus well defined. This results in a broadening of the sharp zero-field resonance into a wide but confined resonance range, which is clearly shown in Fig. 2(b). The double-step-like shape of the I-V curve is only due to the exponential background signal; both the onset and the end of the resonant tunneling regime are marked by a peak in the dI/dV. Thus, the resonance broadening results in a splitting of the dI/dV peaks for increasing transverse magnetic fields. In Fig. 3 the measured dI/dV curves are plotted for various magnetic fields. The splitting is well observed for the $E_0^{\rm acc}$-$E_0^{\rm inv}$ and the $E_0^{\rm acc}$-$E_1^{\rm inv}$ transition. Figure 4 shows the positions of the split peaks versus magnetic field. Because of an overlap of the split peaks for higher subbands difficulties appear in assigning peak positions for increasing magnetic fields and the peaks in dI/dV are washed out drastically. This intensity dependence of the individual peaks can be understood classically. When the trajectory of the tunneling particles in high magnetic fields no longer reaches the target electrode, the tunneling current decreases drastically.

In order to verify the conservation of the canonical momentum, the peak positions in dI/dV were calculated using Eq. (1) for $k_y=\pm k_F$. The distances $d_{0n}=\langle z_0^{\rm acc}\rangle+d_{\rm barrier}+\langle z_n^{\rm inv}\rangle$ are used as a fitting parameter. The mean value $\langle z\rangle$ denotes the average distance of the electrons from the interface and the indices denote the subband resonances. The d values which give the best fit to the experimental data are $d_{00}=350$ Å, $d_{01}=460$ Å, $d_{02}=570$ Å, and $d_{03}=650$ Å. The corresponding results of $\Delta E_\perp/e=\Delta V_b$ are shown in Fig. 4 as solid lines. In this fit, the dependence of the wave vectors $k_F^{\rm inv}$ and $k_F^{\rm acc}$ on the applied bias voltage V_b was also taken into account.

At low magnetic fields, Δk_y is much smaller than k_F, and the term $(\Delta k_y)^2$ in Eq. (1) is small, leading to the linear behavior evident in Fig. 4. Since for the higher subbands the average distance between the electrons and the GaAs-GaAlAs interface is increased, the splitting of the corresponding resonance peaks is larger than the splitting for the transition between the lowest subbands. If the magnetic field increases, the term $(\Delta k_y)^2$ in Eq. (1) will become important, leading to a nonlinear behavior at higher magnetic fields.

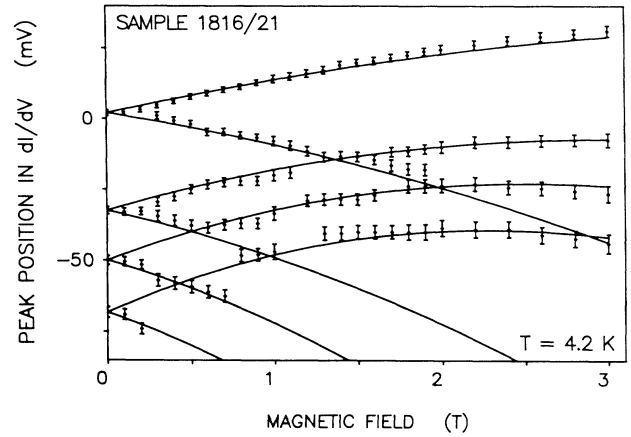

FIG. 4. Fan chart of the measured (dots) and theoretically calculated dI/dV peak positions (solid lines).

The mean values $\langle z\rangle$ can also be determined theoretically. To check the values of d obtained from the fit, the potential distribution and the eigenfunctions of the system were determined self-consistently.[21,22] All calculations were carried out at $B=0$ T, since for low magnetic fields the influence of magnetoelectric hybrid states can be neglected. Comparing the d_{0n} values obtained from the self-consistent results ($d_{00}=340$ Å, $d_{01}=450$ Å, $d_{02}=540$ Å, $d_{03}=610$ Å) with the values from the fit, one gets an excellent agreement. For the lowest two subbands the deviation between experiment and theory is only 10 Å; for the higher subbands the theory matches the experiment within 30 and 40 Å, respectively. Note that, in principle, the values of d_{0n} depend on the applied gate voltage. The numerical results, however, show that this effect is rather small and cannot be resolved within the experimental accuracy. Therefore, the assumption of constant distances d_{0n} is justified when V_b is varied.

Using the fundamental assumption that the canonical momentum is conserved during the tunneling process, we are able to explain the experimental results within a very basic theory. The excellent agreement of the experimental data and the calculated data according to Eq. (1) indicates that our interpretation is correct. Even the conservation of the component of the wave vector parallel to the applied magnetic field, k_x, is a natural consequence of the presented analysis. The symmetry of the problem implies that, if a magnetic field is applied in the x direction, k_x is conserved. This leads to the conclusion that at zero magnetic fields, where the problem is completely symmetric with respect to the z direction, both k_x and k_y

are conserved. Therefore, the $k_\parallel$ conservation deduced from the small linewidths of the $B=0$-T resonance peaks in dI/dV is to be expected.

In addition, our tunneling method not only gives information about the subband energies, but also provides a measurement of the mean values of the electron wave function. From the measured subband energies, the $\langle z \rangle$ values can only be determined by solving Schrödinger's equation. The conservation of the canonical momentum, however, for the first time offers a tool to measure the $\langle z \rangle$ values directly, if k_F is known in the emitter electrode. This method has the advantage that the investigated subband need not to be occupied. On the other hand, k_F can be determined if d_{0n} is known.

In summary, we have studied the momentum conservation rules in tunneling processes between two independently contacted two-dimensional-electron-gas systems. A giant broadening of the subband resonances in the tunneling current is observed in transverse magnetic fields. Through the quantitative explanation of this effect, our experiment unambiguously verifies both the conservation of the canonical momentum and the conservation of $k_\parallel$ in the case of zero magnetic field.

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