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Tunneling from accumulation layers in high magnetic fields

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A theoretical approach to describe tunneling from a two-dimensional electron gas in a magnetic field parallel to the current is compared with experimental data which we have obtained with $GaAs/Al_xGa_{1-x}As$ heterojunctions. Excellent qualitative agreement with the calculated $I(B)$ dependence is reported.

The application of a high electric field at semiconduction interfaces leads to states in which the motion of the electron perpendicular to the surface is bound, resulting in the formation of a quasi-two-dimensional electron system (2D ES) close to this surface. A magnetic field B normal to the electron layer and parallel to the direction of tunneling further quantizes the electron energy into Landau levels. It was proposed by BenDaniel and Duke[1] that tunneling could provide information about these bound states in the surface channel. Starting with detailed measurements in InAs surface accumulation layers by Tsui (Ref. 2, and references therein), a large variety of semiconductor interfaces were studied by the use of tunneling electrons including PbTe,[3] ZnO,[4] Si,[5] InSe,[6] Te,[7] $Hg_xCd_{1-x}Te$,[8] $In_xGa_{1-x}As$,[9] and $Al_xGa_{1-x}As$.[10]

If the bottom of the lowest subband E_0 in the accumulation layer lies above the Fermi level E_F^L of the collecting electrode ($eV_g > E_F^R - E_0$ in Fig. 1 where E_F^R is the Fermi energy in the 2D ES and V_g is the voltage applied), all electrons in the accumulation layer contribute to the tunnel current. For a given voltage $V_g = (E_F^R - E_F^L)/e$, a variation of $B_\perp$ strongly modulates the tunnel current as shown experimentally by Hickmott.[10] We have made magnetotunneling measurements on a number of different samples. These results permit for the first time a direct comparison with a calculation of the tunnel current from an accumulation layer under high magnetic fields.

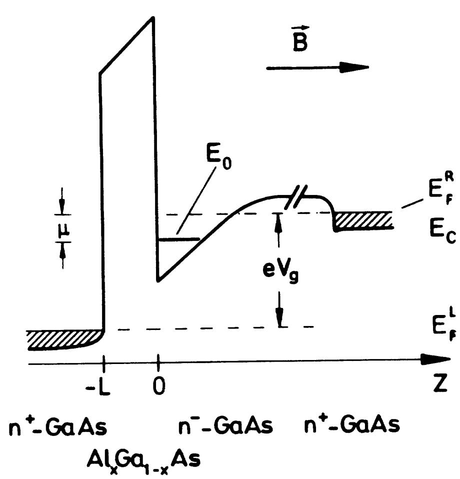

FIG. 1. Spatial variation of the potential energy $E_c(z)$ of an electron at the conduction-band edge under forward bias.

The theoretical description of tunneling from a quasibound state requires the calculation of the electron wave function. Let us consider the z direction to be normal to the junction plane. The potential $V(z)$ describes a quantum well of arbitrary shape separated by a barrier from a halfspace. If the magnetic field B is oriented in the z direction, the symmetry of the problem allows the separation of the motion parallel and perpendicular to the xy plane. The Schrödinger equation which describes the tunnel problem is therefore one dimensional. The wave functions localized in the well form a series $\chi_i(z)$ with energies E_i. Depending on the shape of the barrier (height, thickness) there is a small but finite penetration of the wave function $\chi_i(z)$ into the halfspace. This finite value of the wave function determines the tunnel probability T_i for this quasibound state, which depends only on the energy E_i

$$T = T(E_i) . \qquad (1)$$

In contrast to tunneling from a three-dimensional electrode, where an integration over the energy E has to be performed, the total amount of current for the two-dimensional electrode can be obtained by summing over all eigenstates i weighted by their occupation N_i (Ref. 1)

$$j \sim \sum_i T(E_i) N_i . \qquad (2)$$

The magnetic field dependence of the tunnel current (see Fig. 2) has to be explained in the framework of this simple picture. Baraff and Appelbaum (Ref. 11, and references therein) have pointed out that all parameters describing the accumulation region will be affected by the variation of a magnetic field B perpendicular to the interface. Here we will discuss the variation of the tunnel current as a function of the magnetic field arising from magnetic-field-dependent subband energies E_i. We restrict ourselves to the discussion of the subband $i=0$ using the ansatz of Fang and Howard[12] for the parametrized wave function

$$\chi_0(z) = \left(\frac{b^3}{2}\right)^{1/2} z e^{-bz/2} \qquad (3)$$

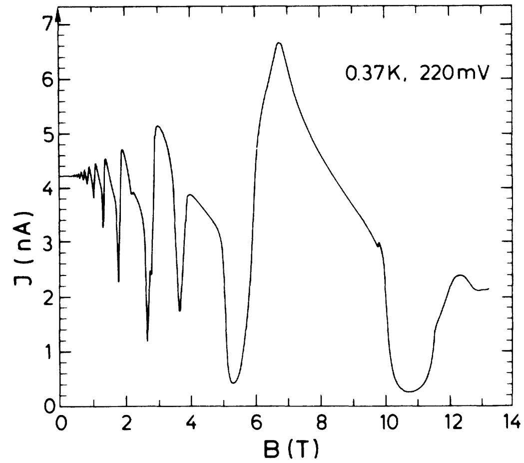

FIG. 2. Tunnel current through a 500-Å $Al_xGa_{1-x}As$ layer with a voltage of 220 mV applied across the barrier, which leads to a mean carrier density of 2.6×10^{11} cm^{-2} in the accumulation layer. The measurements are performed at 0.37 K.

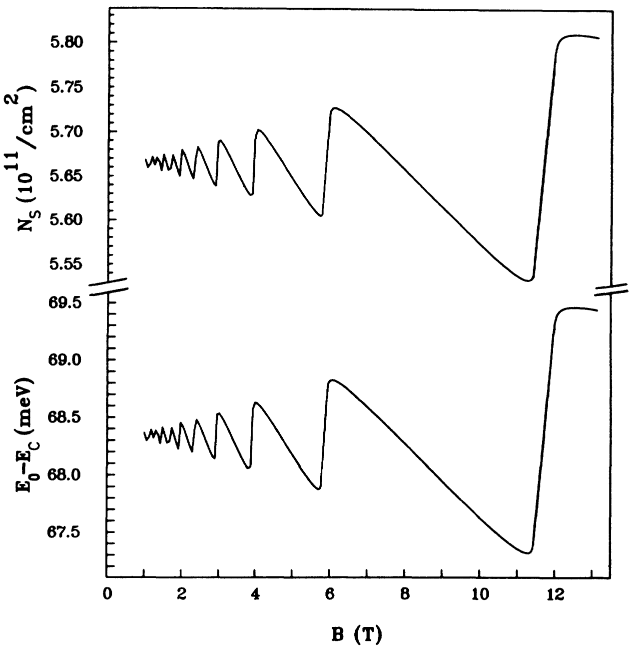

FIG. 3. Carrier concentration N_S and difference between subband energy E_0 and conduction-band edge E_C as a function of the magnetic field B. For details, see text.

with the variational parameter b. The density of states of the two-dimensional electron gas in a magnetic field is assumed to be Gaussian broadened with a linewidth $\Gamma(\text{meV})=0.3\sqrt{B(\text{T})}$ (Ref. 13) and a constant background (5% of the zero-field value). Spin splitting is ignored, however structures in the experimental curves due to the nondegenerate spin levels can easily be understood in the framework of the theoretical concept introduced in this paper. We calculate self-consistently the potential $V(z)$ and the subband energy E_0 as a function of the voltage V_g applied between topgate and backgate. Adopting the model to our experimental situation V_g is kept constant during the sweep of the magnetic field. Thus we can calculate the actual potential shape $V(z)$ as a function of B. Corrections to $V(z)$ due to the finite value of the wave function in the barrier are vanishingly small. Therefore, we use this wave function $\chi_0(z)$ of the self-consistent calculation of the potential $V(z)$ for an analysis of the tunnel current, even though it does not penetrate into the barrier. Using a Wentzel-Kramers-Brillouin (WKB) approximation to calculate the transmission coefficient $T(E_0)$ we obtain

$$T(E_0)\sim e^{-2\tau}, \quad (4)$$

$$\tau=\frac{1}{\hbar}\int_a^b\sqrt{2m^*(V(z)-E_0)}dz\,. \quad (5)$$

a and b are the classical turning points and m^* is the effective mass at the Γ point of the $Al_xGa_{1-x}As$ barrier. The results will show that $T(E)$ is affected by minimal changes ΔE_0 in E_0. Due to the exponential variation of T with respect to E qualitatively similar results will be obtained with any of the theoretical approaches to the transmission probability.

In Fig. 3, we have plotted the carrier concentration N_S and the separation between the subband energy E_0 and the bottom of the conduction band E_C, E_0-E_C, versus magnetic field. Sudden jumps appear for magnetic fields B_ν corresponding to integer filling factors $\nu(B_\nu=N_Sh/2e\nu)$. At these points the index of the highest occupied Landau level changes. Therefore, the chemical potential μ in the 2D ES which is defined as $\mu=E_F^R-E_0$ jumps between Landau levels. For increasing magnetic fields μ decreases suddenly by about $\hbar\omega_c=\hbar eB/m^*$, the energy separation of adjacent Landau levels. Due to a negligible voltage drop between channel and n^+ substrate, the subband energy $E_0=E_F^R-\mu$ is forced to increase if the gate voltage V_g is kept constant. This will change the band bending at the interface, i.e., the electric field across the barrier will increase. Following simple electrostatic arguments we find that in conjunction with the electric field, the carrier density N_S on the two-dimensional plate of this capacitorlike structure has to increase too. Finally the electric subband energy E_0 increases relative to the conduction-band edge at the interface and, therefore, a strong enhancement of the transmission probability is observed (see Fig. 4). It is important to note the size of the induced modulations. Though the 2D quantities N_S and E_0-E_C only change by a few percent, the current $j=T(E_0)N_S$ varies by about 30%.

One of the conceptually simplest structures for studying tunnel currents from accumulation layers at semiconductor interfaces is the layer system shown in Fig. 1.[14] The semiconductor-insulator-semiconductor (SIS) capacitor is grown by molecular beam epitaxy (MBE) on a (100)-oriented Si-doped n^+-type GaAs wafer. It consists of a n^--type GaAs layer ($N_D\approx1\times10^{15}$/cm^3), ≈1 μm thick, an undoped $Al_xGa_{1-x}As$ layer of thickness L and a n^+-type GaAs layer ($N_D\approx2\times10^{18}$/cm^3), 0.1 μm thick which serves as a gate electrode. N_D is the donor concentration in the n-type GaAs layers; $x\simeq0.35$ for the samples used in this work. Immediately after MBE-growth metal

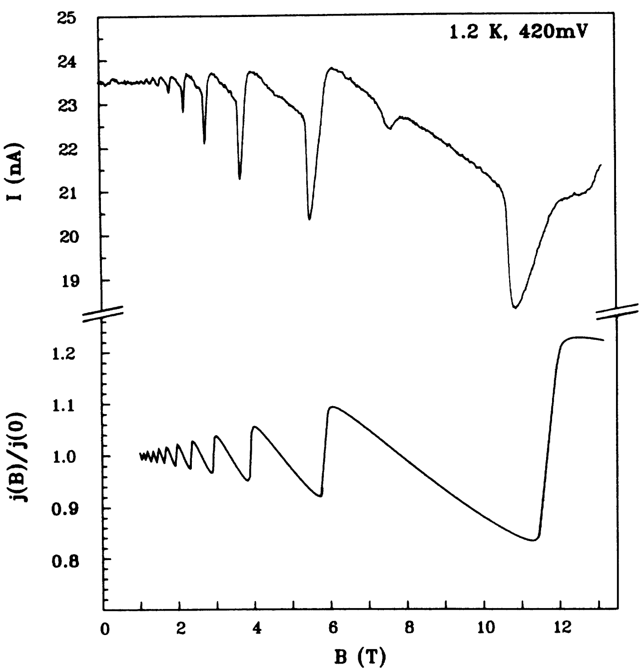

FIG. 4. Measured and calculated magnetic field dependence of the tunnel current I through a 300-Å barrier ($V_g = 420$ mV, $T = 1.2$ K, $N_S = 5.66 \times 10^{11}$ cm^{-2}). The dip at 7.6 T is due to spin splitting which is not included in the calculation.

contacts (AuGe/Ni, 500-μm diameter) are evaporated on the n^+-type GaAs toplayer. We obtain excellent Ohmic contacts(10^{-5}–10^{-6} $\Omega\,$cm^2) with short anneal processes (400 °C, 2 min). Mesa structures are defined by etching (≈ 2 μm depth) using the metal contacts as masks.

For gate voltages above a certain threshold voltage ($V_{th} \simeq 0$ V) an accumulation layer forms at the interface between the n^--type GaAs and the $Al_xGa_{1-x}As$. We have studied the tunnel current from this two-dimensional electron gas through the $Al_xGa_{1-x}As$ barrier varying the layer thickness L from 150 to 520 Å. The temperature dependence of the current was measured and found to be in excellent agreement with the one predicted for tunneling at temperatures far below the thermal emission region.[15] Magnetocapacitance experiments carried out at the same samples prove that only one subband in the 2D ES is occupied. In addition, these experiments show that the Fermi niveaus in the 2D ES and the n^+-type GaAs substrate are aligned.

A common feature of all samples is a pronounced triangular shape of the $I(B)$ curves as predicted by the model. Figure 4 shows a comparison between an experimental $I(B)$ dependence obtained for a 300-Å barrier and the corresponding calculated result, which was normalized to its zero-field value. The gate voltage V_g was taken from the experiment, structural parameters like barrier thickness were taken as specified by the MBE grower. The agreement in the magnetic field position of integer filling factors proves that the theoretical model is a correct description of the entire structure. Without any adjustable parameter, the overall shape of the tunnel current $I(B)$ in the magnetic field regions where the Fermi level is pinned close to the Landau levels is well reproduced, although some dips are observed in the experimental curves at integer filling factors which are not found in the calculated curves. We did a careful analysis of these dips comparing them with magnetocapacitance measurements carried out on the same sample. The interpretation of the frequency dependence of these capacitance data indicates clearly that we have to consider the lateral conductivity σ_{xx}. The electron transport through the n^--type GaAs is inhomogeneous on a microscopic scale (hopping). Arriving at the accumulation layer, the electrons have to be distributed in the xy plane, a transport process involving σ_{xx}. It is known from the quantum Hall effect that this lateral conductivity goes to zero if the Fermi level lies in the region of localized states between Landau levels. This leads to very high series resistances, i.e., the tunnel current decreases strongly.[16] For higher temperatures ($k_BT \sim \frac{1}{2}\hbar\omega_c$) this anomaly vanishes and the $I(B)$ curves get a shape identical to the calculated one. The slope and the absolute value of the current stay nearly constant over a wide temperature range as long as the inequality $k_BT < \hbar\omega_c$ is fulfilled.

In conclusion, we have calculated the magnetic field dependence of the tunnel current from an accumulation layer. We have obtained the relevant parameters to calculate the entire shape of the potential solving the Schrödinger equation for the whole system using a variational method. Using the well-known formula $j = T(E_0)N_S$ the current density j has been calculated in WKB approximation. $I(B)$ measurements on GaAs/$Al_xGa_{1-x}As$ heterostructure devices are shown to be in excellent qualitative agreement with the theoretical calculations. A strong anomaly for integer filling factors is observed and is related to the vanishing lateral conductivity σ_{xx}.

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