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Universal conductance fluctuations in a parabolic quantum well tunable from two- to three-dimensional behavior

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Abstract

Parabolic quantum wells (PQWS) allow the study of the transition between the quantum limit with one two-dimensional (2D) subband occupied and the case of two occupied subbands. During this transition the character of phase coherent loops is changed from being strictly 2D to three-dimensional (3D). The implications for the amplitude and correlation field of universal conductance fluctuations (UCF) were studied experimentally. The population of the second subband is found to manifest itself in both quantities. Possible influences of increased electron–electron scattering and elastic intersubband scattering are discussed. © 1998 Elsevier Science B.V. All rights reserved.

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Parabolic quantum wells (PQWs) have been developed in order to realize three-dimensional (3D) electron gases of high mobility [1]. In suitably designed samples the electronic structure in the PQW can be driven from many occupied subbands (multi-mode conductor) into the two-dimensional (2D) quantum limit [2]. Universal Conductance Fluctuations (UCF) [3] are a well-established quantum phenomenon in mesoscopic conductors. The effect has been investigated experimentally in 3D, 2D and one-dimensional (1D) structures. However, to our knowledge, there have been no investigations of the effect at the crossover between the 2D quantum limit and the case of many occupied subbands. PQWs are especially well suited for investigations in this regime. In this paper, we report on experimental results obtained from the measurement of UCF in PQWs with 1–3 occupied subbands where we expect a crossover from 2D to 3D electron trajectories.

The PQWs were realized by MBE growth using the digital alloy technique [4]. The 76 nm wide well was sandwiched between two $Al_{0.3}Ga_{0.7}As$ barriers with remote doping on both sides. Details about sample growth can be found elsewhere [5]. Hall-bar structures of width $W = 2$ μm were fabricated using a combination of photo and electron beam lithography (see inset of Fig. 1). A Ti/Au Schottky gate was deposited on top. The 0.5 μm-wide potential probes were separated by lengths $L = 1.5$, 2.5, 5.5 and 11 μm. All measurements were carried out in a dilution refrigerator at the base temperature of 30 mK and using standard lock-in techniques.

Fig. 1 shows the total electron density, n_S, and the Hall-mobility, μ_H, as a function of the gate voltage, V_G. The mobilities found here are typically

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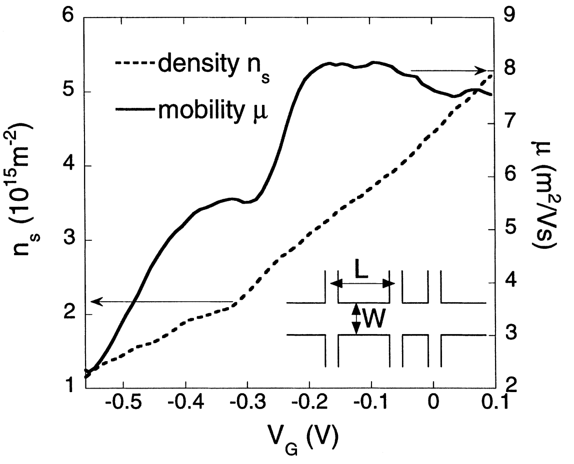

Fig. 1. Electron sheet density and mobility as a function of the gate voltage.

2 times smaller than those of large area samples fabricated from the same wafer. According to Ref. [6] the relative resistance enhancement due to diffuse boundary scattering can be estimated as $l_{el}^{bulk}/(2W)$ which accounts for the factor of 2 in our case (here, l_{el}^{bulk} is the elastic mean free path measured in a macroscopic sample). As discussed in Ref. [7] the structure in $\mu_H(V_G)$ is caused by the occupation of a second subband at $V_G = -0.31$ V and a third subband at $V_G = -0.05$ V.

The electrical transport properties of PQWs can be discussed by introducing relevant length scales. The effective parabolic conduction band profile can be thought of as being caused by a homogeneous volume doping of $N_{3D} = 7.6 \times 10^{16}$ cm^{-3}. On filling the well with electrons of a sheet density n_S their 3D density distribution is to a good approximation constant and equal to N_{3D}. On this basis we find a characteristic 3D Fermi-wavelength $\lambda_F = 38$ nm. We define an effective well width $w = n_S/N_{3D}$ which can be tuned with V_G between 16 and 68 nm. In the case of $w < \lambda_F$ ($n_S < 2.9 \times 10^{11}$ cm) one subband is occupied and transport is two-dimensional. For $w > \lambda_F$ more subbands are occupied and an additional degree of freedom becomes available for electron motion in growth direction. In this sense, the 2D-nature of the system gets lost.

The relevant length scale for electron transport at low temperatures is the elastic mean free path, l_{el}. It ranges from 125 nm at the lowest up to 850 nm at the highest densities as determined from the density and mobility data in Fig. 1. Hence, transport can be described semiclassically and is quasi-ballistic. The phase coherence length l_φ is usually determined from measurements of the weak-localisation correction of the conductivity or from UCF in mesoscopic samples. Our samples were designed such that l_φ is comparable to W and the smallest L and much larger than w. For measurements at low temperatures the effect of finite temperature can be summarized by comparing it with the thermal diffusion length l_T which ranges between 0.8 μm at the lowest and 3.3 μm at the highest densities in our experiment.

For the measurements of the UCF we applied a magnetic field, B, normal to the plane of the PQW and measured the four terminal longitudinal resistance R_{xx} and the Hall resistance R_{xy}. As shown in Fig. 2 the UCF appear as small oscillatory features superimposed on a smooth resistance background which is not symmetric in B due to a small admixture of ρ_{xy} to ρ_{xx}. We first extracted the experimental quantities characterizing the UCF, namely, the amplitude, δG, and the correlation field, ΔB_c. For this purpose we used a 6th order polynomial fit to remove the smooth background, R_{fit}, and determine $\Delta R_{xx}(B) = R_{xx}(B) - R_{fit}(B)$. No UCF are removed by this

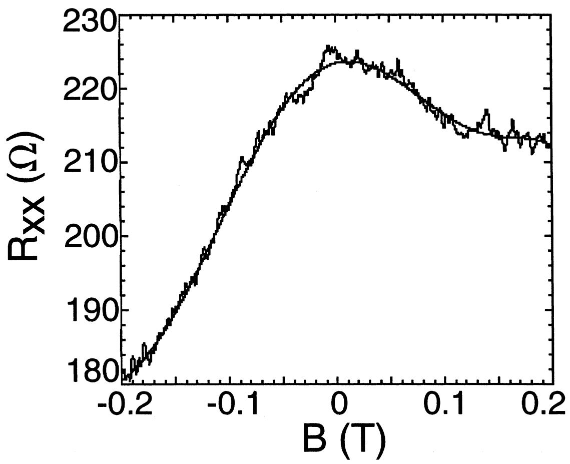

Fig. 2. Longitudinal resistance exhibiting UCF on top of a slowly varying background (smooth line).

technique, since the largest oscillation periods which can be identified as UCF are given by $\Delta B_{\max} \sim \Phi_0/l_{\rm el}^2$ ($\Phi_0 = h/e$), which is 10 mT at typical electron densities and much smaller than the typical field scale of the smooth variations of the background resistance. In the second step we determine

$$\Delta G(B) = \frac{W}{L}\frac{\Delta\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2}, \quad \text{where } \rho_{xx} = \frac{W}{L}R_{xx}.$$

Only the mean value of ρ_{xx} and only the linear part of ρ_{xy} have been used in the denominator. Finally, we determined

$$\delta G = \sqrt{\langle \Delta G(B)^2 \rangle_B}.$$

For $L = 1.5$ μm we find typical values of $\delta G \sim 0.5e^2/h$. Comparing δG for different lengths L we find $\delta G \propto 1/L^{3/2}$ in agreement with the theoretical expectation for a system with $l_\varphi > W$ [8]. The quasi-period ΔB_c was determined from the auto-correlation function [8] to range between 15 (lowest densities) and 2 mT (highest densities). According to the theory valid for systems with $l_\varphi > W$ [8] the correlation field of the UCF is given by

$$\Delta B_{\rm c} = \frac{\Phi_0}{C_1 l_\varphi W} \tag{1}$$

and the amplitude is

$$\delta G = \frac{e^2}{h} \cdot \left(\frac{C_2 l_\varphi}{L}\right)^{3/2}. \tag{2}$$

The quantities C_1 and C_2 are functions of the length ratios $l_\varphi/l_{\rm T}$, $l_\varphi/l_{\rm el}$ and $l_{\rm el}/W$. From the experimental quantities ΔB_c and δG, the phase coherence length can be determined independently. In the absence of any theory treating the case of more than one occupied subband we used Eqs. (1) and (2) and determined the quantities $C_1 l_\varphi$ and $C_2 l_\varphi$ as a function of $V_{\rm G}$, which gives the trend of the l_φ-behavior. The resulting values were averaged over the different contact pairs (different L) to reduce spread statistically by a factor of 2. The result of this analysis is depicted in Fig. 3.

Since both quantities, C_1 and C_2 are of order 1, we can state that the phase coherence length l_φ is of the order of 1 μm in our samples comparable to the geometric width of the Hall bar, W, which

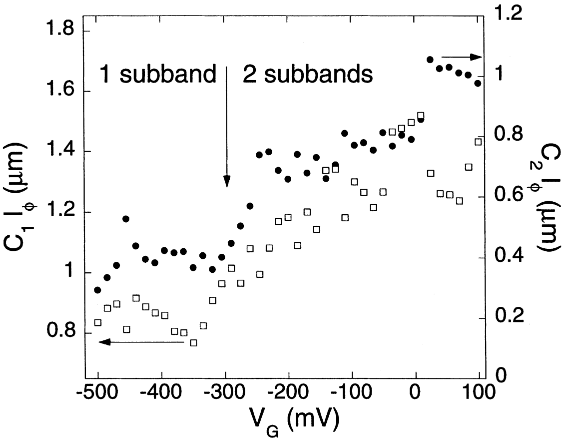

Fig. 3. $C_i l_\varphi$ as determined from the UCF amplitude δG and from the correlation field $\Delta B_{\rm c}$.

justifies application of Eqs. (1) and (2). Since $l_{\rm T} > l_\varphi$, phase coherence is limited by electron–electron scattering events.

It can be seen that both methods lead to a very similar overall behavior of $C_i l_\varphi$ ($i = 1, 2$) with gate voltage. With increasing carrier density $n_{\rm S}$ the phase-coherence length increases as well. Below $V_{\rm G} = -0.3$ V, i.e. just below the occupation threshhold for the second subband, the increase of $C_i l_\varphi$ is retarded but catches up around -0.3 V where the increase is steeper than in average. Comparing the results shown in Fig. 3 with the dependence of the mobility on $V_{\rm G}$ in Fig. 1 the behavior of $C_i l_\varphi$ appears to be qualitatively similar to that of $l_{\rm el}$.

The simplest approach to an understanding of our data is an independent subband model where only the statistical properties of the fluctuations are discussed without any microscopic theory. In this simplified model the two subbands behave as two independently fluctuating channels, each with its own gate voltage dependence. The total amplitude of the fluctuations would then be given by $\delta G = \sqrt{(\delta G_1)^2 + (\delta G_2)^2}$. The associated increase in the measured δG would be given by a factor of $\sqrt{2}$ (for $\delta G_1 = \delta G_2$) or less (otherwise), in rough agreement with the measurement. The correlation field $\Delta B_{\rm c}$ for a system of two independent subbands would theoretically be given by the equation $[\exp(-B \ln 2/\Delta B_{c1}) + exp(-B \ln 2/\Delta B_{c2})]/2 =$

1/2. In the case $\Delta B_{c1} = \Delta B_{c2}$ the correlation field would be unchanged.

These arguments imply that both elastic intersubband scattering and collisions between electrons in different subbands are neglected. If we take collisions of electrons between different subbands into consideration the phase space for this kind of interaction is considerably increased when the second subband becomes populated. The effect would be a reduced phase coherence length and reduced values of δG and ΔB_c. This effect counteracts the increase in δG discussed above. Elastic intersubband scattering would also affect phase coherence but, to our knowledge, no theories are available.

Measurements of the same sample in tilted and parallel magnetic fields show that the character of the electron trajectories changes from 2D to 3D behavior [9]. These results will be discussed in a separate publication.

In conclusion, we have investigated UCF in a PQW at the crossover from one to two occupied subbands. The occupation of the second subband manifests itself in the UCF amplitude and correlation field.

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