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Numerical Simulations of Magneto Transport in Dot Array Systems at High Magnetic Fields

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We use a network model for modeling the magneto transport in quantum dot array systems. We study numerically the role of Fermi level pinning for the Landau level (LL) de-population at the quantum point contacts which couple the dots. We find that for the case of Fermi level pinning by the 2DEG the resulting sawtooth behavior of the Fermi level leads to deviations from the linear dependence of the LL energies versus magnetic field, if those energies are obtained from de-population experiments by sweeping the split gate voltage.

1. Introduction

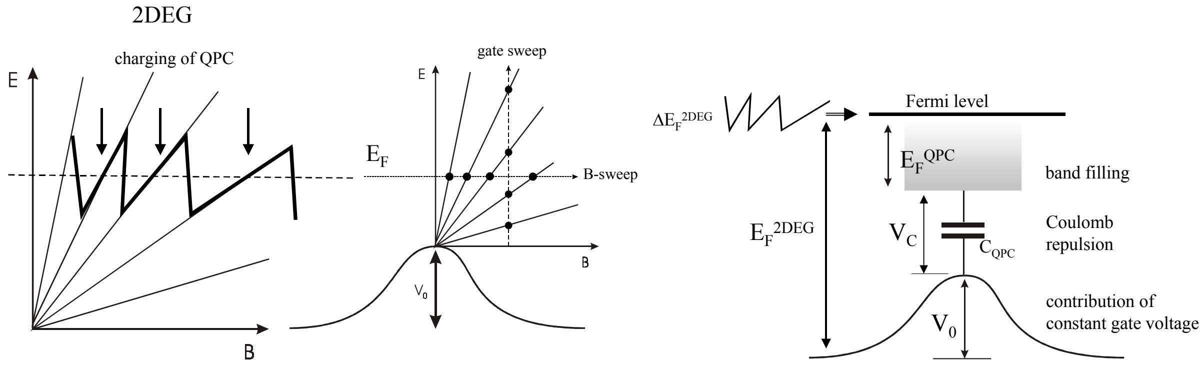
Quantum dot (q-dot) array systems are of potential interest for device applications based on quantum coherence. In addition, the possibility of achieving a g-factor enhancement allows new concepts in the field of spintronics. The overall performance of a q-dot is determined by the properties of the quantum point contacts (QPC) which couple the dot to the environment. Concerning the g-factor enhancement a major question is whether or not such an enhancement, which appears in a 2DEG [1], also persists in the vicinity of the saddle potential of a QPC. This particular question is important if using such devices for e.g. spin injection.

There has been done already a lot of work on the issue of g-factor enhancement in dot array systems [2-4]. The q-dot arrays used in the experimental work are formed by doubly corrugated quantum-wires which are fabricated with the standard split-gate technique on the surface of a high mobility GaAs/AlGaAs wafer. The electron density and mobility are 3.8 x 10^{15} m^{-2} and 57 m^2/Vs, respectively. The length and the width of the individual dots are 1.0 and 0.6 μm, respectively, and the dots are coupled by 0.3 μm wide QPCs. From de-population experiments by sweeping the split gate voltage the energy of the spin split Landau levels (LLs) has been determined as a function of the magnetic field. From these analysis an effective g-factor for the QPC region has been extracted. For the lowest LL the g-factor appears to be further enhanced as compared to the 2DEG, but shows a similar enhancement like in the 2DEG for the higher LLs. However, when approaching the pinch-off situation at the QPC the g-factor enhancement drops significantly below that one in the pure 2DEG.

The purpose of this paper is to investigate whether or not population/de-population effects at the QPC could be responsible for that strange behavior of the effective g-factor. To be precise, it is not the purpose of this paper to give a theoretical model for the g-factor enhancement it self, but to look for possible reasons for it’s variation as a function of the q-dot population at different magnetic field. The basic procedure in this context is to use a model for magneto transport in order to simulate sets of magneto transport data and perform a similar analysis of these data like done with the experimental data.

2. The transport model

For numerical simulations of the magneto transport in the high magnetic field regime we use a recently developed network model [5], for which the first concept was already presented at the previous symposium 3 years ago [6]. The physical basis of the network is a system of magnetic bound states, which are created by long range potential fluctuations in real samples and couple at the saddle points by tunneling. This coupling is formally treated like a back scattering process in the edge channel picture so that the nodes of the network resemble interconnected QHE samples. For these a position dependent filling factor due to the laterally varying carrier density is used. Without going into further details we point out, that the sample structures are designed by shaping the lateral carrier density profile, which is "filled" into the network. In this way any arbitrarily shaped realistic sample structure can be modeled in terms of R_{xx}, R_{xy} or any mixed case with arbitrarily chosen contact configurations. Gated regions like the QPCs appear as depressions of the lateral carrier density distribution. This model has been extended in a way, that the carrier density at the QPC can respond to changes in the environment like changes in the Fermi level pinning "outside" the QPC. Two cases have been studied: (i) The Fermi level is kept at a fixed value for the whole system and (ii) using a fixed carrier density in the 2DEG and calculating the Fermi energy, which then is used for calculating the carrier density at the QPC. Both cases have a quite different impact on the transport behavior. Specially case (ii) leads to the known sawtooth like oscillations of the Fermi energy versus magnetic field. These oscillations are introduced to the QPC, which leads to a carrier density at the QPC which oscillates according to E_F.



a) b) c)

Fig.1 a) schematic representation of the LLs versus magnetic field in the 2DEG. Fermi level pinning in the 2DEG leads to a sawtooth like behavior like schematically indicated by the bold line. b) The LLs are shifted up in energy by the saddle potential V_0. The horizontal and vertical lines indicate the 2 possibilities for de-populating the LLs (magnetic field sweep and gate voltage sweep). c) Schematic model for the response of the QPC to changes of the Fermi level in the 2DEG (charging/de-charging effect).

Fig.1a shows the situation in the 2DEG and Fig.1b shows the situation at the QPC. There are 2 modes for experiments: One is performing a magnetic field sweep at constant gate voltage and the other is a gate voltage sweep at constant magnetic field. In order to account for a possible change of the Fermi level and an associated change of the carrier density at the QPC, a model as shown in Fig.1c has been used. It can be understood as follows: In an initial situation we have a Fermi energy E_F, a saddle potential V_0 and a local Fermi energy at the QPC of $E_F^{QPC} = E_F - V_0$. If E_F starts to increase, additional charge in brought into the QPC, which increaes the local Fermi energy in the QPC. However, this additional negative charge will bring up also a coulomb repulsion which is labeled with V_C. In this way the model assumes that not necessarily all of the change of E_F appears as a change of the local Fermi energy at the QPC. Therefore we have to assign some sort of local capacitance to the QPC, for which no accurate estimates exist at present. For the simulations shown below a local capacitance of C_{QPC}^{-1}= 1mV/10^{11}cm^{-2} was used. However, this number is not decisive at this point since it just determines, to what extend a movement of E_F causes band filling at the QPC or not. At present we want to investigated this effect only on a qualitative level.

3. Results and discussion

In this section we show simulations of gate voltage sweeps at different magnetic fields. This is done for both a constant Fermi energy (E_F = 14 meV) and for a sawtooth like Fermi level as obtained from using a constant carrier density of n = 4x10^{11}cm^{-2} in the 2DEG.

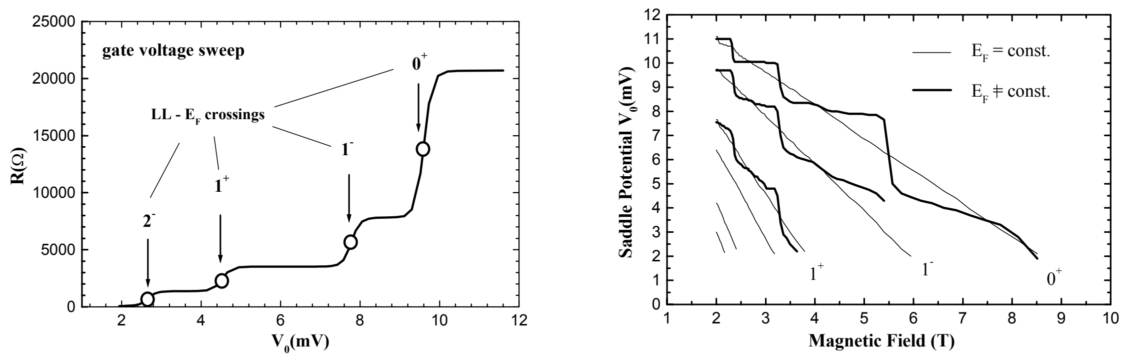


Fig.2 left: Typical result for a gate voltage sweep at B=3T. The points of inflection represent the positions of the saddle potential, at which the labeled spin split LL matches the Fermi level. Right: Magnetic field dependence of the points of inflection for both, a constant Fermi level and a sawtooth like Fermi level (Simulation parameters: n = 4x10^{11}cm^{-2} ,$\Gamma = 0.5 \cdot B^{1/2}$, g*=20)

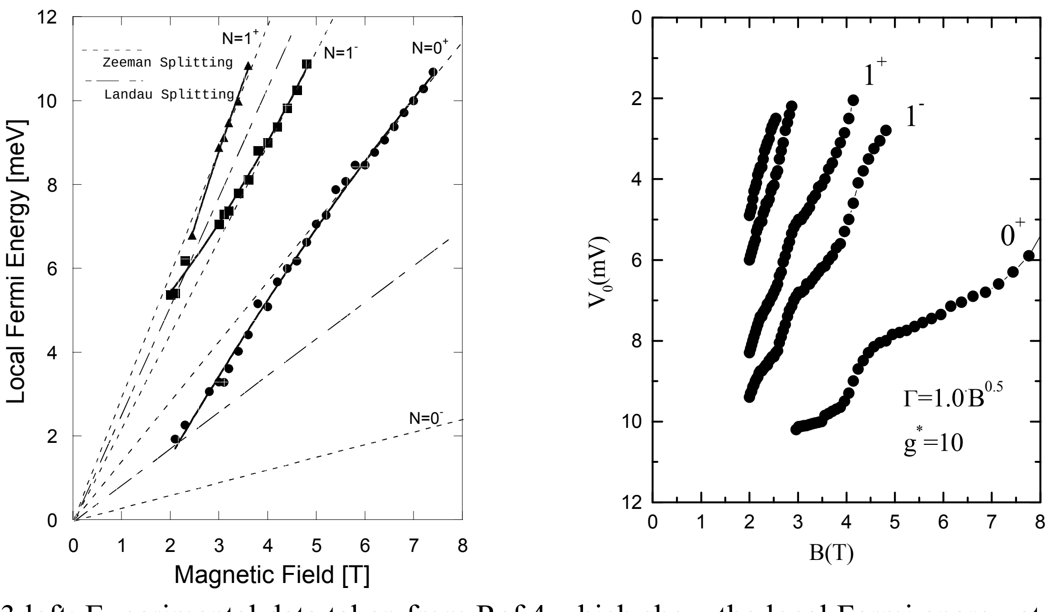


Fig.3 left: Experimental data taken from Ref.4 which show the local Fermi energy at the QPC at which the de-population of various LLs occurs as a function of magnetic field. Right: equivalent plot to Fig.2 right with simulation parameters as indicated in the figure. The V_0-axis is plotted upside down in order to match the representation of the experimental data on the left.

The plateaus shown in the left part of Fig.2 appear if LLs at the QPC are getting depleted by pushing up V_0, which corresponds to increasing the negative gate voltage experimentally. The crossing of the LLs at the QPC with the Fermi level can be identified by the points of inflection on the slope of the resistance traces. Since the LL energies shift with magnetic field, also these crossing points shift on the V_0 scale. On the right hand side of Fig.2 we show the magnetic field dependence of these LL crossings. For the case of a constant Fermi energy this dependence appears as straight lines and can be identified with the magnetic field dependence of the LLs. However, in the case of the sawtooth like behavior of the Fermi level strong departures from this linear behavior appear. The flattened parts of the traces indicate the charging period of the QPCs from the rising Fermi level in the 2DEG. In this period the magnetic de-population is partly compensated by the charging and therefore also the gate voltage dependence is slowed down (flattened). Fig. 3 shows a comparison with experimental data from Ref.4. As can be seen, a reasonable overall agreement is achieved for a LL-broadening $\Gamma = 1.0 \cdot B^{1/2}$, an effective g-factor of $g^*=10$ and a carrier density in the 2DEG of $n = 4x10^{11}cm^{-2}$. Just the slope of the experimental lowest spin-split LL suggest a larger g-value, which was determined to be $g^*=20$ [4]. It is important to note, that the calculation is done for a constant g-factor, but still departures from a straight line like in the experiments appear. This suggests that indeed some sort of charging effects like suggested by the model might take place in the real experiments. Further investigations are needed to confirm this findings.

4. Summary:

We have applied a network model for magneto transport in dot array systems and studied the influence of Fermi level pinning on the de-population of LLs at the quantum point contacts. We have investigated the split gate potential versus magnetic field at which several LLs experience de-population. We have found that a pinning of the Fermi level in the surrounding 2DEG can lead to significant departures from a linear dependence.

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References:

[1] R. J. Nicholas, M. A. Brummell, J. C. Portal, K. Y. Cheng, A. Y. Cho, and T. P. Pearsall, Solid State Commun., **45** (1983) 911.

[2] N. Aoki et al., Proc. 10th Int. Conf. on Narrow Gap Semiconductors, published by Institute of Pure and Applied Physics, Tokyo, 2001

[3] N. Aoki et al., Physica E **13**, 769 (2002)

[4] N. Aoki et al., Physica B **314**, 235 (2002)

[5] J. Oswald, A. Homer, Physica **E11/4**, 310 (2001)

[6] J. Oswald, A.Homer, P.Ganitzer, Microelectronic Engineering **47**, 31 (1999)