POSSIBLE DEFINTION OF QUANTUM BITS IN COUPLED QUANTUM DOTS

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ABSTRACT

In this work we investigate laterally defined quantum dots confined in AlGaAs/GaAs heterostructures comprising a two-dimensional electron gas with extremely high mobility and large phase relaxation length. Our goal is to study the intricate mechanisms of wave function interaction in these artificial molecules. We probe the wave function entanglement of two coupled quantum dots by applying transport spectroscopy at ultra low temperatures. We determine the strength of this tunnel coupled mode and monitor the magnetic field dependence. This mode is the key element for any quantum computational realization with semiconductor quantum dots.

1. INTRODUCTION

The elementary devices in modern computer architectures are CMOS transistors. During the last years considerable effort was undertaken in investigating the limits of operation of classical transistors. One of the results of this continuous size reduction is the single-electron-transistor (SET). It consists of a small electron island – also called quantum dot – coupled to leads by tunneling barriers. Due to the ultra small capacitance the Coulomb interaction of single electrons in this quantum dot and in the leads is becoming dominant. The repulsive electrostatic force thus blocks electron transport through the island. This so-called Coulomb-blockade (CB) can only be overcome by an additional electrostatic energy. Supplying this energy by gate electrodes then enables single electrons to tunnel sequentially through the SET. At first these SETs only could be operated at temperatures of some 10 mK [1], but by now operation of metallic SETs at temperatures up to 100 K is reported [2]. The smallest quantum dots we were able to build to date are shown in Fig. 1(a) (the dots are formed in the narrow wire). Starting material in this case was a doped Silicon-on-Insulator material. However, so far most of the basic research on quantum dots is performed at temperatures below 100 mK, employing III/V-heterostructures as the material of choice.

The main advantage of heterostructures is the high degree of perfection with which its electronic, photonic and phononic properties can be tailored. These materials enabled ground breaking work which demonstrated that quantum dots in the few electron limit show not only charge quantization, but reveal a discrete energy spectrum similar to real atoms[3,4]. The main difference to natural atoms is the confinement potential, which is parabolic for quantum dots. Nevertheless, this finally led to the term 'artificial atom'. Consequently the combination of two of these 'atoms' creates an artificial molecule. The extraordinary advantage of such a 'molecule' is that it is completely controllable by the experimenter, allowing to balance the number of electrons as well as the degree of coupling of the wave functions.

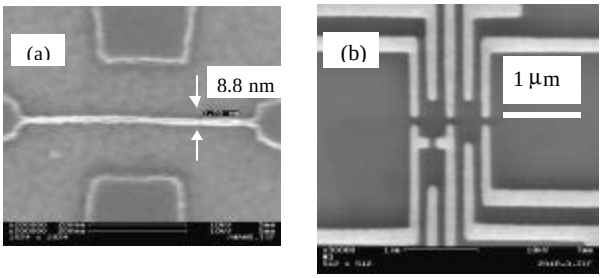

Figure 1. Quantum dots realized in in a wire of doped Silicon-on-Insulator material (a) and in a GaAs/AlGaAs-heterostructure (b): Fabrication of Silicon-dots with diameters down to only 15 nm is possible. The large electron density suppresses so far coherent modes to evolve. III/V-heterostructures with multiple Schottky-gates and high mobility two-dimensional electron gases allow the investigation of phase coherence.

Naturally the wave function coupling leads to a tunnel coupled state, which can be probed in transport [4] and microwave spectroscopy [5]. This coupled state can be regarded as the elementary quantum bit (qubit) [6] in semiconductor devices as suggested by Loss and DiVincenzo [7]. In comparison to a common bit, qubits depend on quantum mechanical states $|0\rangle$,$|1\rangle$, which can be superimposed to forming entangled states. The fundamental advantage of implementing qubits in 'artificial molecules' is the promise of up-scaling and possible integration in semiconductor systems. Here we want to address the question whether it is experimentally possible to create such qubits within a coupled quantum dot device. We present how this coherent state is generated and how it can be probed, as suggested [8,9]. The underlying aim of this research is the determination of phase relaxation times, the different dissipation mechanisms in coupled

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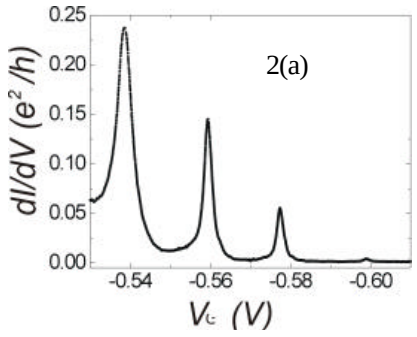
dots, and – in the long term – to include the spin degree of freedom in these systems.

Processing of the laterally gated quantum dots used in this work, starts off from high-mobility two-dimensional electron gases (2DEG) in a GaAs/AlGaAs-heterostructure. Optical lithography is used to fabricate ohmic contacts and bond pads. The Schottky gates used to define the quantum dots (Fig. 1(b)) are written by electronbeam lithography and evaporating a *100* nm metal layer. For characterizing the 2DEG magnetotransport measurements are performed, yielding an electron density of 2×10^{-11} m^{-2} and an electron mobility of *80* m^2/Vs. The measurements shown were obtained from a two dot device for which we estimate the total number of electrons in the two dots to be about 12 and 33. The phase coherence length in the 2DEG is 2.5 μm, i.e. comparable to the device size.

2. TRANSPORT MEASUREMENTS ON COUPLED DOTS

2.1 Electrostatic Interaction of Two Dots

The focus of early experiments on coupled quantum dots was to study the electrostatic interaction [10]. The first measurements in dots with a larger number of electrons (*N ~ 300 - 500*) accurately described the transition from weak to strong electrostatic coupling. In contrast to transport measurements on single quantum dots, where mostly the conductance is traced under gate voltage variation (see Fig. 2(a)), double dots require a more elaborate scheme. This is realized by determining the conductance through the coupled dots under shifting the two dot's electrostatic potentials by two gate voltages. The resulting three-dimensional data set is commonly represented in a gray scale plot also termed charging diagram, as seen in Fig. 2(b).



The CB-region (gray) is intersected by the conductance resonances (black), when the two dots are placed in series. Then electron transport is only possible when the CB of both dots is overcome. In this data set the interdot coupling is weak. The coupling strength is defined by the interdot capacitance C_{id}, which is in this case on the order of some 10 aF. By varying this capacitance the charging diagram is distorted in such a way that the resonance points form a hexagonal lattice instead of the d trapezoidal lattice shown in Fig.2(b).

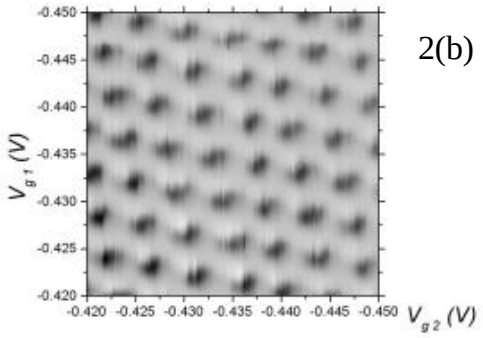


Figure 2. Coulomb blockade measurements in a single (a) and a coupled dot system (b). For characterizing single dots a simple line trace is sufficient, while for the coupled dots a gray-scale plot is of advantage. In (a) each resonance corresponds to the tunneling of single electrons, increasing the total number of electrons on the dot by one. The conductance's magnitude in (b) is defined by $G = 0$ (gray) and $G > 5$ μS (black). Here the two dots are weakly coupled, which can be identified by clear resonance pattern (trapezoidal shape).

2.2 Coherent Modes in Artificial Molecules

In contrast to the electrostatic interaction we now want to focus on how the wave functions in the individual quantum dots couple, when the transmission through the central barrier is tuned. As we have seen the charging diagram allows the complete characterization of the coupled dot system. The coupling then is defined by the interdot capacitance, while when considering the exchange of electrons between the dots the conductance G has to be taken into account. The tunneling matrix elements t are then proportional to $t \sim G$. Since the double dots are placed in series, electron flow is minutely controlled by the center gate. This allows to directly tune the overlap of the wave functions in the two dots and to create an entanglement.

By carefully adjusting this overlap in the range of $G = (0 - 0.4)e^2/h$ the tunnel splitting of the ground state can be monitored. In Fig. 3(a) a selected conductance resonance in the regime of strong coupling is shown in a logarithmic representation. In the crossing point the two main peaks have maximum amplitude, i.e. the wave function overlap is largest in this region. In addition to the electrostatic interaction we find here evolving sub-peaks in the shoulders of the two main peaks (see arrows in Fig. 3(a)), since the total number of electrons is small. It has to be noted that we observe in this crossing point two ground states with a different total number of electrons.

The sub-peaks correspond to the tunnel split levels, while the main resonances are the ground states. This also agrees considering the energies of the excited states in the individual dots. The first dot's charging energy is fairly large, hence only the excited states of the large dot have to be taken into account.

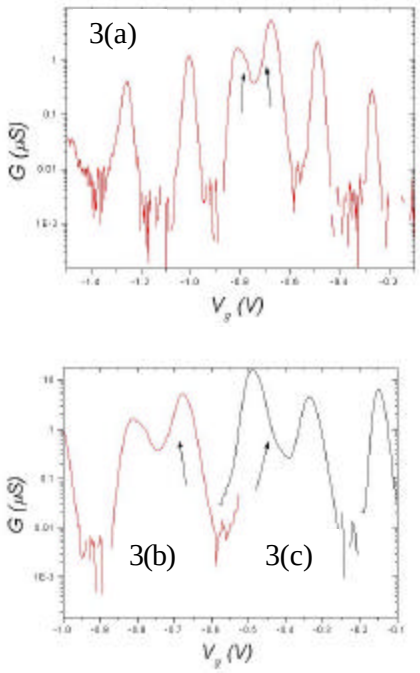


Figure 3. (a): Trace taken from a charging diagram in the limit of strong coupling between the two dots. This logarithmically plotted conductance resonance intersects two crossing points where the electrostatic interaction and the tunnel coupling is maximum. The arrows indicate the tunnel split states in the shoulders of the ground states (main peaks). (b) and (c): Magnified part of the crossing point with the two main peaks shown in (a). The tunnel split states in the shoulders can be tuned by application of an external gate voltage (arrows).

The charging energies of this double dot are determined to be $E_C^A = 0.9$ meV and $E_C^A = 3.1$ meV. Since these are still on the order of *0.3* meV, only the tunneling split state with an energy of *0.1* meV can carry a current. While the bath temperature of the dilution refrigerator in these measurements was maintained at *25* mK, the electron temperature remained at *100* mK. This non-zero temperature in the leads allows electrons to tunnel through the additionally available states. From this experiment it is not clear, whether the tunneling split states are the symmetric or anti-symmetric states. Commonly one assumes that the ground state is symmetric. This necessarily not has to be the case, since the exact spin orientation can be more complex than in our simple estimation. More elaborate schemes of detection have to be applied to reveal the exact nature of this ground state.

In Fig. 3(b,c) we magnified the two central peaks in the crossing point. The additional peaks in the shoulder are clearly seen (marked by arrows). Varying the back gate voltage – an additional gate situated *0.5* mm below the sample's surface – the overlap of the wave functions is changed and the tunnel split level is shifted from the left to the right peak. As we have seen it is possible to probe this formation of a coherent mode. An estimation of the relaxation time by the relation $t = e/I$, gives values in between *10 – 100* nsec, which represents the transfer time of the electrons. Comparing this value to the typical frequencies or excitation rates found in microwave spectroscopy of *10 – 100* psec, this yields a possible rate of $10^3 - 10^4$ operations per cycle. This is a crucial value for all approaches to quantum computation.

3. QUENCHING TUNNEL COUPLED STATES

3.1 Magnetic Field Dependence

One of the key questions naturally is how to manipulate the coherent state or in other words, how to address the qubit in the artificial molecule. Basically there are three different ways to achieve this goal: The first one is to directly tune the tunnel coupling by changing the appropriate gate voltage, as was demonstrated in Fig. 3. The second method is to apply a magnetic field which effectively reduces the coupling. [9]. The third method to probe the entangled dot states is to address it by photons in the GHz-range.

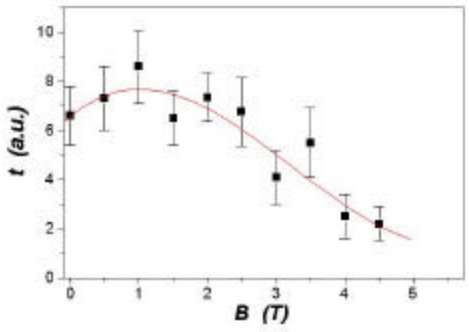


Figure 4. Plotted is the magnitude of the tunnel coupling *t*. The boxes represent the measured values – the error bars result from the number of crossing points analyzed. The solid line represents a polynomial fit [9].

In this last section we want to focus on how to manipulate the tunnel coupling by application of a magnetic field perpendicular to the plane of the 2DEG. A simple understanding for this approach is given by the reduction of the wave function overlap. The magnetic field leads to an effective reduction or quenching of the radii of the individual wave functions.

In order to determine this quenching we measured several charging diagrams at different magnetic field strength. Then the amplitudes

of the ground and the tunneling state are compared to the background conductance and normalized to the zero field value. The arrow bars result from analyzing multiple crossing points. As seen the experimental trace shows a dip towards zero magnetic field and from $B = 1$ T to higher fields the coupling drops to zero. We have to note that the measurements reveal the tunnel coupling t and not the exchange energy J. However, it is clearly seen that the tunnel splitting is quenched by the magnetic field. The solid line is a polynomial fit to the experimental data. This trace agrees quite well with the theoretically predicted curve, although no dip around $B = 0$ T is expected [9]. Within the error bars, however we obtain good agreement. Further work is required to obtain more information about the exact spin orientations of the electrons in the ground state.

3.2 Electron Spin in Quantum Dots

The main problem is that the electronic relaxation time of electrons in quantum dots is short compared to spin relaxation times, thus limiting the number of operations possible [11]. Recently it has been shown that the electron spin in single dots can be controlled with great precision, thus allowing to study the Kondo effect in 'artificial atoms' [12,13]. The Kondo effect is known from Solid State physics for a couple of decades already. It basically represents an intricate spin dependent scattering mechanism. In quantum dots the localized spin of the electrons in a dot hybridize with the electron spins in the leads, which opens an additional transport channel. This creates the so-called zero bias anomaly, i.e. transport becomes feasible even when the quantum dot is tuned into the CB regime. Furthermore, it seems to be possible to manipulate spin states in large quantum dots by electron spin resonance in the GHz-range [14]. This is achieved by applying a sufficiently large magnetic field, which creates a spin split state in the dot when the lowest Landau level is reached. In addition to the conventional CB the spin-spin interaction has to be taken into account. A microwave field of several GHz is able to induce spin flips locally, giving rise to electron transport through states which are otherwise not accessible. Combining these two approaches will create the possibility to study the spin relaxation times in single and coupled quantum dots, which in turn might enable the preparation of coherent modes with an enhanced life time.

4. SUMMARY

We have given a detailed description of how to realize a coherent mode in a double quantum dot device. Such a coherent mode can be regarded as the essential quantum bit, being the building block of any quantum computational device in a semiconductor. It still remains to be shown how many operations on these particular qubits are possible and whether it indeed can be integrated with in more complex schemes. In the measurements presented the spin degree of freedom was not yet addressed. We note that applications of II/VI-heterostructures allows the integration of magnetic two-dimensional electrons gases [15]. The further development of this basic research will show, if the concepts of quantum computation can be applied successfully on the 'artificial molecules'. In any case this work will lead to a detailed understanding of the fundamental properties of these quantum mechanical systems.

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5. REFERENCES

[1] Ashoori, R C., *Nature* 379, 413 (1996).

[2] A. Tilke, R.H. Blick, H. Lorenz, J.P. Kotthaus, D.A. Wharam, Applied Physics Letters, in press (1999).

[3] Proceedings of the Advanced Study Institute on *Mesoscopic Electron Transport*, edited by Sohn, L.L., Kouwenhoven, L.P., Schön, G., Kluwer (1997).

[4] Blick, R.H., Pfannkuche, D., Haug, R.J., von Klitzing, K., Eberl, K., *Physical Review Letters* 80, 4032 (1998).

[5] Blick, R.H., van der Weide, D.W., Haug, R.J., Eberl, K., *Physical Review Letters* 81, 689 (1998); Oosterkamp, T.H., Fujisawa, T., van der Wiel, D.W., Ishibashi, K., Tarucha, S., Kouwenhoven, L.P., *Nature* 395, 873 (1998).

[6] Williams, C.P., Clearwater, S.H., *Explorations in Quantum Computing*. Springer-Verlag New York Inc., 1998.

[7] Loss, D., DiVincenzo, D.P., *Physical Review A* 57, 120 (1998).

[8] Burkard, G., Loss, D.P., DiVincenzo, *Physical Review B* 59, 2070 (1999).

[9] Burkard, G., Loss, D., DiVincenzo, D.P., *Physical Review* B, in press (1999), cond-mat/9808026; Burkard, G., Seelig, G., Loss, D., *cond-mat/9910105.*

[10] Waugh, F.R., Berry, M.J., Mar, D.J., Westervelt, R.M., Chapman, K.L., Gossard, A.C., *Physical Review Letters* 75, 705 (1995); Blick, R.H., Haug, R.J., Weis, J., Pfannkuche, D., von Klitzing, K., Eberl, K., *Physical Review B* 53, 7899 (1996).

[11] Kikkawa, J.M., Smorchkova, I.P., Samarth, N., Awshalom, D.D., *Science* 277, 1284 (1997). Kikkawa, J.M., Awshalom, D.D., *Physical Review Letters* 80, 4313 (1998).

[12] Goldhaber-Gordon, D., et al., *Nature*, 391, 156 (1998); Cronenwett, S.M., et al., *Science*, 281, 540 (1998); Simmel, F., Blick, R.H. , Kotthaus, J.P., Bichler, M., Wegscheider, W., *Physical Review Letters* 83, 804 (1999).

[13] Blick, R.H., et al., *Physical Review B Rapid Communications B* 57, 12685 (1998).

[14] Smorchkova, I.P., Samarth, N., Kikkawa, J.M., Awschalom, D.D., *Physical Review Letters* 78, 3571 (1997).