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Few-electron quantum dots in InGaAs quantum wells: Role of fluctuations

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We study the electron transport properties of gated quantum dots formed in InGaAs/InP quantum well structures grown by chemical-beam epitaxy on prepatterned substrates. Quantum dots form directly underneath narrow gates due to potential fluctuations. We measure the Coulomb-blockade diamonds in the few-electron regime of a single dot and observe photon-assisted tunneling peaks under microwave irradiation. A singlet-triplet transition at high magnetic field and Coulomb-blockade in the quantum Hall regime are also observed. © 2011 American Institute of Physics. [doi:10.1063/1.3574540]

Materials with large spin-orbit coupling, such as InGaAs, are currently of considerable interest due to potential spintronics applications. Although lateral quantum dots (QDs) are routinely demonstrated in GaAs, the InGaAs material has not been suitable for this technology because of poor quality Schottky gates. Two groups have applied the split gate technique on InGaAs structures using dielectrics between the gates and the heterostructure.^{1,2} Prepatterned substrate technology allows to reduce leakage and exclude dielectrics, i.e., use Schottky gates rather than gates on dielectric. In addition, this technology is promising for optical applications and g-factor engineering.³ Here, we study the formation of single QDs in the few-electron regime in an InGaAs quantum well (QW) under a narrow gate. We find that potential fluctuations play an important role in the formation of the QDs, as it was the case for incidental dots in GaAs.^{4–6} We perform a comprehensive study of these dots using standard magnetotransport techniques.

We start with a sample containing a 5 nm thick InGaAs QW in InP, 70 nm below the surface. NiAuGe Ohmic contacts are located on the edges of a 5 μm wide active region. The split gate layout, similar to that of Ref. 7, is shown in Fig. 1(a). Several devices had similar QD characteristics, and here we present one of them in which we have achieved the one-electron regime. As shown schematically in Fig. 1(b), the QD forms directly under the 160 nm wide gate labeled g, when the gate voltage V_g is brought close to the pinch-off voltage. The remaining gates are biased passed their pinch-off to deplete the region in the upper left corner of Fig. 1(b). As the electron density under gate g gradually decreases to zero, a small puddle of electrons survives as a result of a fluctuation in a similar way as reported in.^{4,5} We measure conductance G as a function of V_g at 0.3 K using standard lock-in techniques. After illumination, the electron density in the ungated areas is $6 \times 10^{15} \text{ m}^{-2}$, and the mobility is $\approx 2 \text{ m}^2/\text{Vs}$, as estimated from two-terminal measurements.

Figure 1(c) shows that Coulomb-blockade (CB) peaks occur in the conductance as V_g is swept. The peak positions change very little when the voltage on any other gate is changed (ratio $\sim 1/30$, not shown), which confirms that the QD is formed under gate g. The CB peaks in Fig. 1(c) correspond to charging of the last potential fluctuation.

In order to confirm that we operate in the few-electron regime, we apply a drain-source bias, V_{ds} , and observe typical CB diamonds in dI/dV_{ds} [Fig. 1(d)]. We have determined from measurements where $|V_{ds}|$ goes up to 35 mV and V_g down to -0.85 V (not shown) that the last diamond never closes. We conclude that we have completely emptied the dot. We also observe faint lines that terminate in the $N=0$ region [arrows in Fig. 1(d)]. These are not excited states of the QD. Detailed studies confirm that they originate from mesoscopic modulations in the density of states in the leads^{8,9} and completely disappear if a 1 T perpendicular magnetic field is applied. From the size of the first CB diamond, which does not contain quantization energy, we find a charge-

FIG. 1. (Color online) (a) Electron micrograph of a split gate device nominally identical to the ones measured. Black dots indicate Ohmic contacts. TiAu gate electrodes, labeled a, b, c, t, and g, climb on the top facet of the 5 μm wide active region (the side walls of the ridge structure are light gray). (b) Close up schematic showing how a QD can form inside a fluctuation underneath gate g. The gray area in the upper left corner is depleted of electrons, as the voltages on the other gates are passed pinch-off. (c) CB in the few-electron regime. $V_{exc}=20 \text{ } \mu\text{V}$. (d) dI/dV_{ds} in the V_{ds} - V_g plane showing CB diamonds. White (black) is low (high) dI/dV_{ds} . Arrows point to lines from mesoscopic modulations of the density of states in the leads. (e) Dependence of the first CB peak on microwave frequency. Inset: half the splitting between the satellite peaks vs microwave frequency and fit.

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FIG. 2. (a) dI/dV_{ds} at $V_{ds}=4$ mV vs B where the line due to the triplet excited state is indicated by an arrow. White (black) is low (high) dI/dV_{ds} . (b) B -dependence of dG/dV_g in the few-electron regime. Black (white) is negative (positive) dG/dV_g . (c) dG/dV_g map showing charging effects in the QHE regime. The values of ν indicated are the average filling factors in the 2DEG directly under the gate. White (black) is negative (positive) dG/dV_g . The dashed line is an example of charging feature near $\nu=2$.

ing energy $U=6$ meV, which corresponds to a dot diameter $D=e^2/(4\epsilon_{InP}U)\approx 60$ nm, where $\epsilon_{InP}=12\epsilon_0$. The slopes of the diamond edges allow the extraction of the dimensionless constant $\alpha_g=0.247$, which converts the V_g axis into electrochemical potential. The spacings between the first few CB peaks in Fig. 1(c) are consistent with a shell structure filling. Indeed, the $N=2$ valley (corresponding to a filled s shell of the artificial atom) is larger than both the $N=1$ and $N=3$ valleys.

To confirm α_g from an independent experiment, we shine microwaves on the QD. We measure the evolution of the first CB peak from Fig. 1(c), which survives even at 6 K (not shown), in the presence of a cw microwave irradiation. The results are in Fig. 1(e). At low power ($\sim\mu$ W), we find a pair of satellites on the sides of the conductance peak, as shown in Fig. 1(e). At higher powers, multiple-photon absorption is observed, so an additional pair of satellites develops further away from the CB peak (not shown). In order to confirm that the satellites originate from photon-assisted tunneling,¹⁰ we repeat the experiment at several frequencies f between 30 and 50 GHz. We fit each trace to a sum of three Lorentzians (not shown) and extract the spacing between the satellites. The half-splitting, Δ , is linear in f over the entire frequency range [Fig. 1(e) inset], which provides an independent measurement of $\alpha_g=0.236$ that compares well with that extracted from CB diamonds. The fact that two satellites are observed signifies that the QD is symmetrically coupled to both leads.

We now examine how the conductance evolves when a magnetic field, B , perpendicular to the two-dimensional electron gas (2DEG) is applied. Figure 2(a) shows the evolution of the CB peaks between $N=1$ and $N=2$ from Fig. 1(c) as a function of B at $V_{ds}=4$ mV. The presence of a nonzero bias across the dot results in a current stripe between the $N=1$ and 2 regions. The extra line indicated by an arrow in Fig. 2(a) within the current stripe originates from transport through an excited state. For a dot with two electrons, the exchange energy between them results in a singlet ground state and a triplet excited state, hence the excited state fea-

ture seen in Fig. 2(a) is ascribed to the triplet. At $B=0$ T, the singlet-triplet gap is $\epsilon_{ST}\sim 3$ meV (i.e., ~ 5 times larger than in GaAs dots¹¹). Transport through the triplet state occurs at smaller V_g as B grows, and a singlet-triplet transition occurs at $B\sim 5$ T. However, the signal decreases significantly at such high fields, so it is difficult to resolve the transition itself and to determine whether there is an avoided crossing. A singlet-triplet transition in a few-electron lateral InGaAs/InAlAs QD has been reported in Ref. 2.

To investigate the role of fluctuations at larger electron numbers, we look at a large overview of dG/dV_g in the V_g - B plane. The results are shown in Figs. 2(b) and 2(c). In Fig. 2(b), the CB peaks curve up as a function of B . As the electron number increases, the conductance peak amplitude may contain information about the change between the singlet and spin-polarized phases.¹² Amplitude modulations are seen in Fig. 2(b). However, charging effects that will be described below play an important role in our case.

Figure 2(c) shows the dG/dV_g diagram all the way up to $V_g=0$. Such a large range of V_g allows one to study what happens as the average electron density under the gate increases. Flat regions, corresponding to plateaus in G , are seen whenever the electron density under the gate is such that the filling factor ν is constant. The cases of $\nu=4$ and 2 are indicated in Fig. 2(c). In addition to flat regions, there are sets of parallel lines in Fig. 2(c) that correspond to charging of isolated compressible regions arising from potential fluctuations in the quantum Hall effect (QHE) regime. Similar charging effects have also been observed in other systems.^{13–17} The average vertical offset ΔV_g between five lines [the dashed line in Fig. 2(c) is an example] in the V_g - B plane on the hole side of the $\nu=2$ region at $B=4$ T allows us to estimate the average charging energy $U=\alpha_g\Delta V_g=2$ meV, where the value of α_g at $B=4$ T is 0.075 from a CB diamond in the V_{ds} - V_g plane (not shown). Assuming a circular dot, the average fluctuation diameter in this regime is $D=e^2/(4\epsilon_{InP}U)\approx 190$ nm.

From the QD sizes extracted at $B=0$ T and in the QHE, the lateral extent of potential fluctuations lies in the 60–190 nm range. A more quantitative estimate of the QD fluctuation (~ 20 meV) is obtained from the chemical potential change between the first CB peak and the point where the conductance background rises rapidly. Using the model from Ref. 18, this can be converted into a Ga composition change of 5.3% for a fixed QW thickness of 5 nm or a QW thickness change of 1.2 nm (corresponding to ~ 4 monolayers) for a fixed Ga composition of 47%. However, these figures seem excessively large for typical structures. Photoluminescence measurements of a planar undoped QW (not shown) reveal a peak with a full width at half maximum of 7 meV, which translates into an average electronic potential fluctuation of ~ 4 meV. This converts into a Ga composition change of $\sim 1\%$ or QW thickness fluctuations of ~ 1 monolayer.

Another approach to estimate the average energy scale of the fluctuations is to consider measurements of transport mobility as a function of density. In Ref. 19, such measurements on a 10 nm thick QW gave a threshold density of $\sim 1\times 10^{15}$ m⁻² below which the mobility drops to zero, signifying that electrons are localized in potential fluctuations. From the density at the mobility threshold, we estimate an average potential fluctuation energy of ~ 5 meV, which is comparable to that of our current work. Dopants in the actual

structure studied here have an average spacing ~ 20 nm, so there are between 9 and 90 dopants over the area of the QDs formed in fluctuations. If the doping is inhomogeneous, it can lead to potential fluctuations, but this is unlikely to produce one that is 20 meV deep.

Schottky barriers on InP are not as good quality as compared with GaAs. In the processing, there is no step to attempt to control native surface oxide prior to gate metallization. This could lead to non uniformity in the electric field from the gates, hence the potential fluctuations. But such fluctuations from Schottky barrier problems cannot explain why a single dot pattern in the center of a split gate design on an InAsP QW broke down into three QDs in the center of the ungated region (not shown).

Another possibility is that the fluctuations in the QW could originate from roughness at the back interface between the InP substrate and the grown InP, which is 160 nm below the InGaAs QW. Surface states may be introduced by the oxide mask used in the prepatterned substrate growth. The substrate is baked prior to the growth, and this process may leave patches of impurities behind, leading to electron density changes in the InGaAs QW. The final microscopic origin of the single QD formed by the deepest fluctuation (~ 20 meV) is not clear at the moment. It may be the result of the combined effect of several mechanisms listed above.

In summary, we have achieved a few-electron QD in a sample with an InGaAs QW defined by a single gate. We have characterized the dot using several common transport phenomena, namely, CB diamonds in the few-electron regime, transport through the $N=2$ triplet excited state, photon-assisted tunneling, and charging of potential fluctuations in the QHE regime. The results in this paper confirm that fluctuations play an important role in QD formation in gated III–V structures. Such fluctuations may be advantageous in forming smaller multiple dot devices with fewer gates with spacing on the order of the fluctuations scale.

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