Integer Filling Factor Phases in Vertical Diatomic Artificial Molecules

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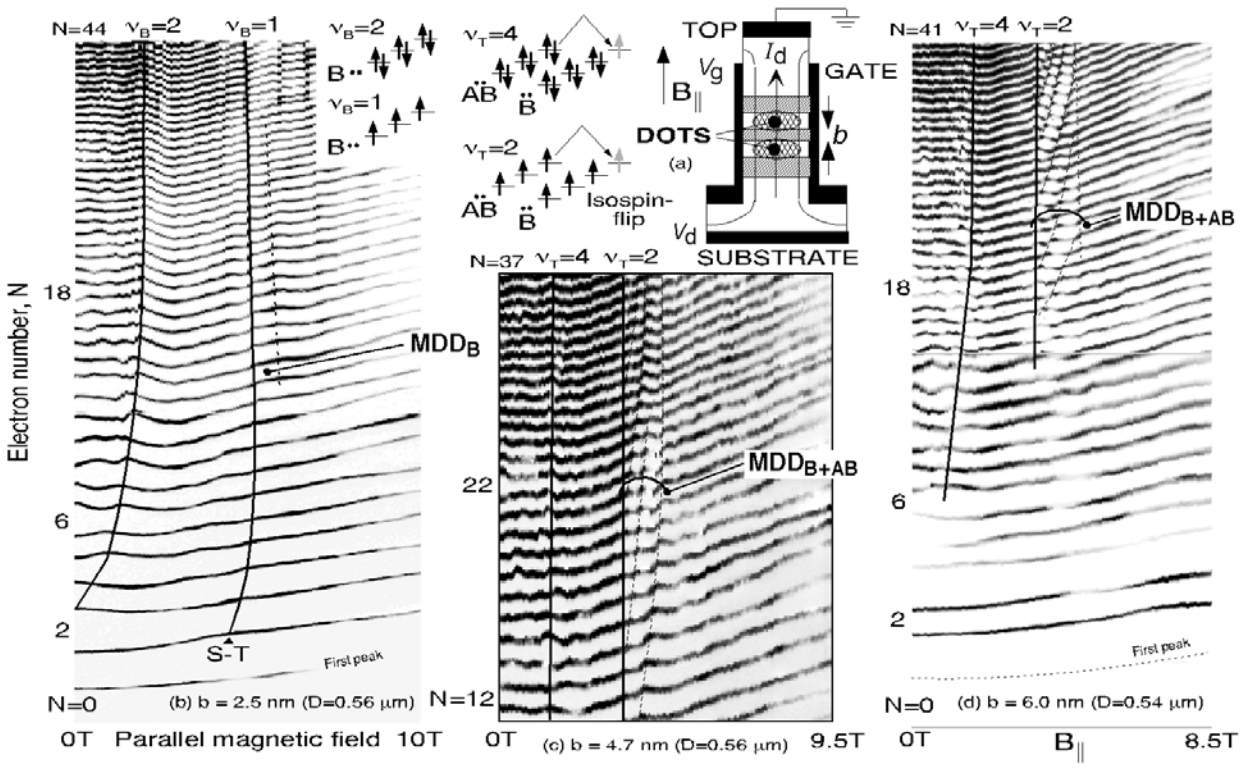
We investigate integer filling factor phases of many-N-electron (up to ~40) vertically coupled semiconductor quantum dot artificial molecules (AM's) for different values of the inter-dot coupling [1]. The experimental results are analyzed within local-spin density functional theory (LSDFT) [2], and we determine a simple lateral confining potential law that can be scaled for the different coupling regimes. Maximum density droplets composed of electrons in both bonding (B) and anti-bonding (AB), or just B states are revealed, and interesting isospin physics (e.g. "isospin-flip" transitions) occurs that may also be relevant to double quantum well bilayer systems.

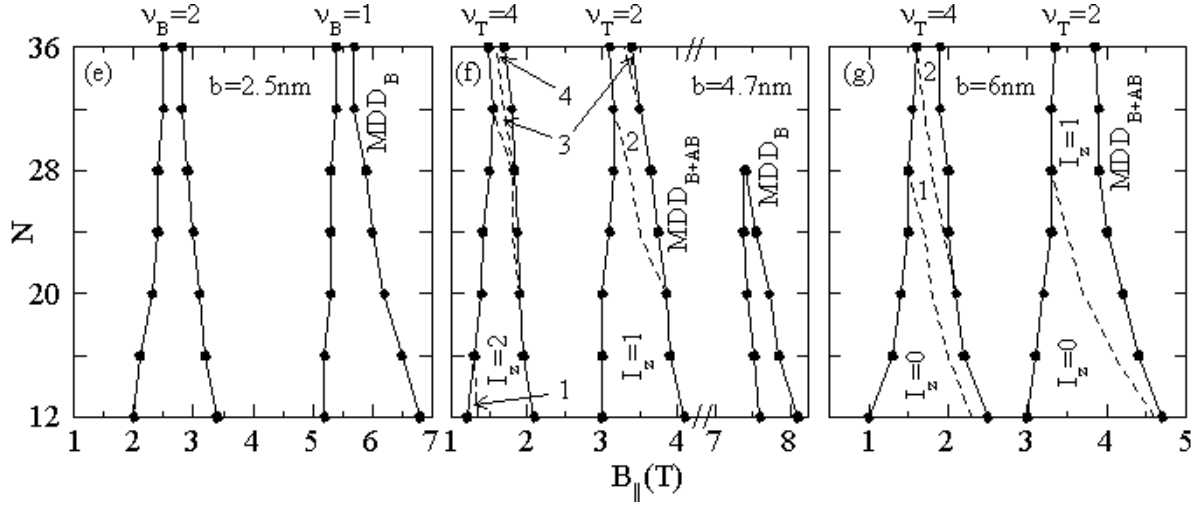
(a) The AM devices are fabricated from a triple barrier structure with a central barrier thickness, b, between 2.5 nm (strong coupling) and 6.0 nm (weak coupling) [1]. The current (I_d) flowing through two dots located inside circular mesas (diameter, D<1 μm) is measured at a temperature ~100 mK as a function of voltage between the substrate and top contact (V_d~0.2 mV), and voltage on the gate (V_g). The magnetic field ($B_{//}$) is applied parallel to the current.

(b-d) Experimental $B_{//}$-N phase diagrams for AM's with b=2.5, 4.7, and 6.0 nm showing evolution of Coulomb oscillations (ground state electrochemical potentials). (b) is strikingly similar to a single dot phase diagram. We identify two threshold lines marking the end of the Fock-Darwin level crossings (filling factor, ν_B=2), and the start of the spin-polarized compact maximum density droplet (MDD_B, ν_B=1). Only B states are relevant. The ν_B=1 line originates from the N=2 singlet-triplet (S-T) transition. (c) and (d) are clearly very different to (b) since now AB electrons play a role as the inter-dot coupling is reduced. We can identify the onset of two cohabiting MDD's- one is made of B states (MDD_B), and the other is made of AB states (MDD_{AB}), so we call this phase MDD_{B+AB} (ν_T=2 i.e., ν_B=1 + ν_{AB}=1). In the MDD_{B+AB} phase, there are features (some connected by dashed lines) that we argue are due to the depopulation of AB-states. Cartoons of the arrangement of electrons in B and AB single particle states, for certain integer filling factors are shown as insets.

(e-g) Calculated $B_{//}$ -N phase diagrams for QM structures with b=2.5, 4.7, and 6 nm. The low and high field boundary of each integer filling factor phase of finite width is drawn. *Only values corresponding to N=4M (M=3-9) are meaningful here*, and we assume the two dots are identical. The effective lateral harmonic oscillator potential has strength $kN_B^{-1/4}$, where k=6.91 meV is deduced from a fit to the onset of MDD_B in (b), and N_B(N_{AB}) is the number of electrons in B (AB) states at 0 T. This we found crucial to achieve a good quantitative description of the phases. Consistent with the experimental data, as the inter-dot coupling is reduced, we find the stability of the MDD_B decreases, and the MDD_{B+AB} phase appears in which isospin transitions occur. Within certain phases (ν_T=4 and 2), regions of different isospin, I_Z=(N_B-N_{AB})/2, are identified by LSDFT, and I_Z is generally found to increase with N and $B_{//}$. Additionally, we discuss the range of stability of the phases, the ν_B=2 phase for the b=2.5 nm AM, and the ν_T=4 phase (ν_B=2+ν_{AB}=2) for the b=4.7 and 6.0 nm AM's for which LSDFT predicts isospin transistions that are 'spin-flip-driven'.

[1] D G Austing et al., Physica B **249-251**, 206 (1998).
[2] M Pi et al., Phys. Rev. Lett. **87**, 066801 (2001).


N=44 ν_B=2 ν_B=1
ν_B=2
ν_B=1
ν_T=4
ν_T=2
Isospin-flip
TOP
GATE
DOTS
(a)
SUBSTRATE
V_g
I_d
V_d
$B_\parallel$
b
N=37 ν_T=4 ν_T=2
N=41 ν_T=4 ν_T=2
Electron number, N
18
6
2
N=0
22
N=12
MDD$_B$
MDD$_{B+AB}$
S-T
First peak
(b) b = 2.5 nm (D=0.56 μm)
(c) b = 4.7 nm (D=0.56 μm)
(d) b = 6.0 nm (D=0.54 μm)
0T
Parallel magnetic field 10T
9.5T
8.5T


ν_B=2
ν_B=1
ν_T=4
ν_T=2
(e)
b=2.5nm
(f)
b=4.7nm
(g)
b=6nm
MDD$_B$
MDD$_{B+AB}$
I_z=2
I_z=1
I_z=0
N
36
28
20
12
$B_\parallel$(T)