Creating quantum dots by charge density fluctuations

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A quantum dot (QD) is a semiconductor nanostructure in which an electron is confined in all three spatial directions thus resulting into a discrete zero-dimensional (0D) energy spectrum. An ideal QD is characterised by a deep, close to parabolic confinement potential that can accommodate several equally spaced energy levels [1]. Such a confinement can be achieved in semiconductor structures by different techniques including atom diffusion and implantation [2,3], nanolithography [4], electrostatic gating [5,6], self-assembly [7], and colloidal synthesis [8]. This work describes a novel method to create a QD. We show that nanoscale spatial fluctuations of charge inside a semiconductor can be induced by randomly distributed interstitial ions and produce a confinement potential with a rich spectrum of 0D energy levels. Our theoretical model reproduces our experimental findings well, and provides further insights into some recent results concerning the observation of QD-like spectra in experiments of resonant tunnelling in bulky (>1μm) semiconductor devices with quantum wells [9-11].

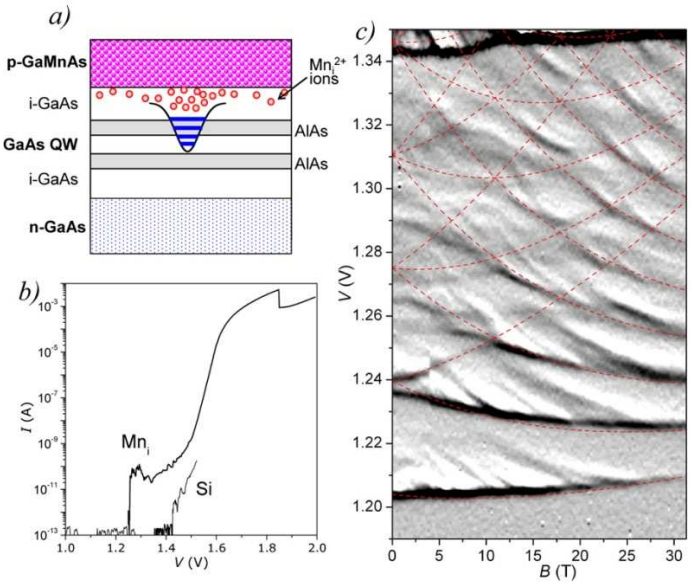

Fig.1 *a*) A sketch of the sample with schematic profile of the electrostatic potential created by a nanocluster of positive (ionised donor) ions placed near the QW. *b*) Typical I(V) of p-i-n RTD with electrostatic QDs created by thermally diffused Mni and MBE grown Si. *c*) Grey-scale plot of the conductance for p-i-n RTD with a p-(GaMn)As layer as a function of the applied bias and magnetic field applied parallel to the current. Dashed lines represent the fit by the Darwin-Fock energy spectrum.

In order to study a potential created by a random charge distribution in a semiconductor structure, we have carried out two sets of experiments with samples depicted schematically in Fig. 1 a). The first type of experiments involves the diffusion of interstitial Mn (Mn_i) from the p-type GaMnAs layer towards the quantum well. Using controlled annealing [11] we created a layer of randomly distributed positively charged Mn_i^{2+} ions electrostatically separated from the diffusion source (GaMnAs p-type layer). In the second sets of experiments, we used GaAs resonant tunnelling diodes (RTDs) in which we introduce a few layers of disordered positive charge (Si^+ ions) during MBE growth.

The layers were processed into circular mesas of diameter 200 μm. Measurement of voltage-current characteristics of our samples revealed sharp resonances for both annealed GaMnAs RTDs and GaAs RTDs with Si dopping [Fig. 1 b)], which are typical for tunnelling via a series of single quantum states. Resonances in the GaMnAs RTD are shifted by ~150mV towards lower biases by the reduced hole chemical potential of GaMnAs material. In strong magnetic fields (up to 32T) applied parallel to the current (perpendicular to the QW plane) we observed a clear diamagnetic shift of the first resonance (ground state) with orbital momentum L = 0, and equally spaced states with L = 1…9 (Fig. 1c). The spectrum shows striking resemblance to the Fock-Darwin spectrum of an ideal 2D harmonic oscillator in a perpendicular magnetic field B (red lines in Fig. 1c), which arises from QDs [12] .

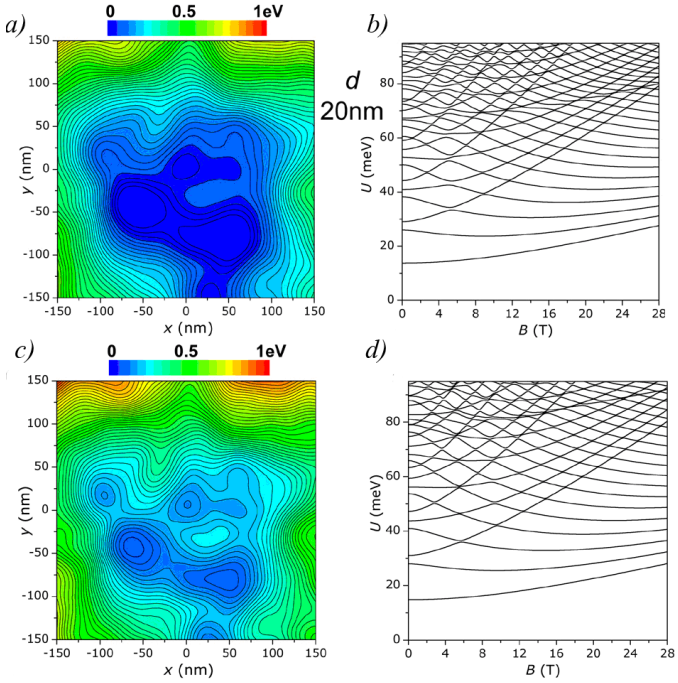

Fig. 2. Numerical simulation of electrostatic potential for *d* = 20nm that is induced by the randomly distributed *a)* Mn_i ions after annealing, or *c)* Si ions in 10 layers. *b*) and *d*) represent the energy spectra of an electron confined in the deepest minimum of the potential shown in *a), b).*

To support our experimental results we simulated numerically the distribution of Mn_i^{2+} and Si, and then calculated the corresponding potential induced by a random set of ions. In the first case, the positions of individual Mn_i in the plane perpendicular to the growth were defined by random numbers corresponding to ‘‘white noise’’ of uniform distribution, with the ion density along the growth axis z given by the diffusion profile C(z):

$$C(z) = C_0 erfc\left(\frac{z}{2\sqrt{Dt_A}}\right),\ D = D_0 \exp\left(-\frac{Q}{k_B T_A}\right), \quad (1)$$

where C_0 = 5x10^{19} cm^{-3} is a typical concentration of Mn_i in the (GaMn)As for 3% of Mn [13], D is the Mn_i diffusion coefficient, D_0 = 3x10^{-4} m^2/s, Q = 1.5eV [14], and T_A=150^{o}C and t_A=3 hours are the annealing temperature and time, respectively. We neglect Coulomb interactions between the Mn_i ions since they have a low concentration in the intrinsic GaAs layer for these annealing conditions. The numerical simulations involved 2x10^6 Mn_i^{+2} ions occupying a volume of 5000 x 5000 x d nm^3, where d is the distance from the central QW plane to the (GaMn)As/GaAs interface. In the second case, the same amount of randomly distributed Si ions with the same in-plane coordinates formed 10 layers with equal numbers of ions spread to an area 5000 x 5000 nm^2.

The results of our simulations are summarized in Fig. 2, which illustrates the potentials induced by random sets of ions a),c), and the corresponding energy spectra for the obtained potentials b),d). For both types of ions distribution, sufficiently large fluctuations of charge density induce a few deep potential minima [see Fig. 2 a),c)]. By solving numerically the 2D Schrödinger equation of an electron in one of these minima in the presence of a perpendicular magnetic field B, we obtain the magnetospectrum shown in Fig. 2 b),d). It is clearly seen that our calculations are in very good agreement with experimental energy spectrum in Fig. 1 c). Remarkably, our results do not depend qualitatively on the method of formation of random distribution.

In summary, we have found that a random distribution of ions in a (GaMn)As p-i-n RTD leads to the formation of well-defined GaAs quantum dots with a very deep confining potential. We observe a rich spectrum of Fock-Darwin-like states, with high orbital angular momenta. By adjusting the annealing conditions and/or the separation between the p-(GaMn)As layer and the GaAs QW, it should be possible to control the depth of the QD potential and the characteristic spacing of its electronic energy levels [11]. Our approach could be exploited to form low-dimensional confinement potentials in functional spintronic devices containing (GaMn)As or other materials, and to study fundamental science, e.g., imaging the wave functions of QDs containing several electrons.

References

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