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Spatial mapping of the electron eigenfunctions in InAs self-assembled quantum dots by magnetotunneling

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Abstract. We use magnetotunnelling spectroscopy as a non-invasive probe to produce two-dimensional spatial images of the probability density of an electron confined in a self-assembled semiconductor quantum dot. The images reveal clearly the elliptical symmetry of the ground state and the characteristic lobes of the higher energy states.

Self-assembled quantum dots (QDs) are nanometer-sized clusters, that are formed spontaneously in strained semiconductor heterostructures. They can confine the motion of an electron in all three spatial dimensions [1]. The strong confinement in the QD gives rise to a set of discrete and narrow electronic energy levels similar to those in atomic physics. Experimentally, the quantized energy levels of a given potential can be probed using various spectroscopic techniques. The corresponding wave functions are much more difficult to measure. We report an experimental study of the spatial distribution of the wavefunction probability density of electron states in InAs/GaAs self-assembled quantum dots (QDs) by magnetotunnelling spectroscopy.

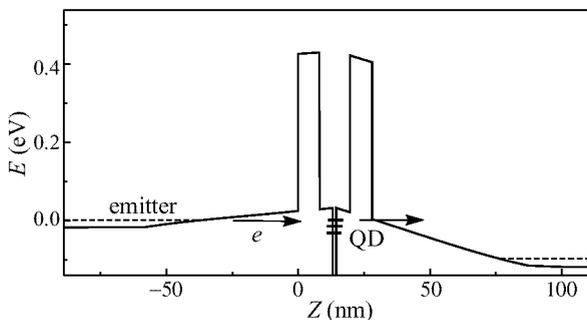


Fig. 1. Schematic conduction band profile under an applied bias of an n-i-n GaAs/(AlGa)As double barrier resonant tunneling diode incorporating InAs self-assembled quantum dots (QDs).

The InAs QDs are embedded in a n-i-n, resonant tunnelling diode. The samples were grown by molecular beam epitaxy on a GaAs substrate with the orientation (311)B. Figure 1 shows a schematic energy band diagram for our device under bias voltage. We observe series of resonant peaks in the low-temperature ($T = 1.5$ K) current–voltage characteristics, $I(V)$, of the diode, corresponding to carrier tunnelling into the dot states. Pronounced current features appear at biases as low bias as 55 mV. They are superimposed on a rising background

current and cannot be resolved for $V > 200$ mV. The amplitude of each resonance exhibits a strong dependence on the intensity of B , applied parallel to the growth plane. In particular, with increasing B , the low-voltage resonances decrease steadily in amplitude, whereas the others have a non-monotonous magnetic field dependence.

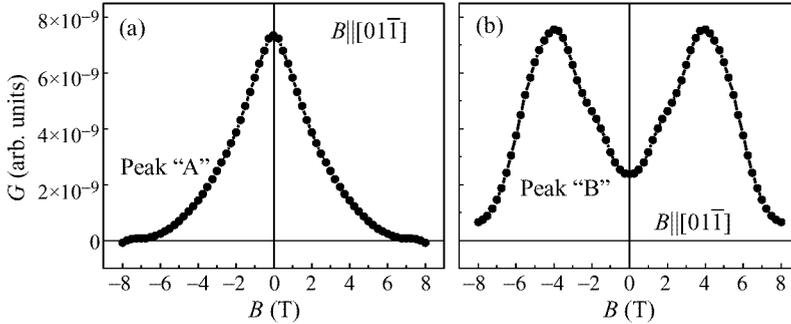


Fig. 2. Dependence of G on magnetic field for B parallel and antiparallel to $[01\bar{1}]$ for the different QDs states.

Figure 2 shows clearly two characteristic types of magnetic field dependence: type “A” shows a maximum on $G(B)$ at $B = 0$ T followed by a steady decay to zero at around 8 T; type “B” shows a broad maximum at ~ 4.5 T, followed by a gradual decay to zero.

Figure 3(a) shows the $I(V)$ characteristics in an in-plane magnetic field of 4.5 T. The first curve (circles) is for $B \parallel [01\bar{1}]$; the second curve (triangles) is for $B \parallel [\bar{2}33]$. We have also determined angular dependence of the peaks current. The results are plotted in Fig. 3(b) for the peaks “A” and “B”. The main effect to be noted from Fig. 4 is the dependence of the current as a function of the in-plane magnetic field orientation.

We can understand the magnetic field dependence of the features in terms of the effect of B on a tunnelling electron. In the experiment, carriers tunnel through a barrier into the dots in the presence of a magnetic field, \mathbf{B} , perpendicular to the current, \mathbf{I} . If x and z indicate the directions of \mathbf{B} and \mathbf{I} , respectively, then when carriers move from the emitter into the dot, they acquire an in-plane momentum

$$\Delta k_y = eB\Delta s/\hbar \quad (1)$$

from the action of the Lorentz force, where Δs is the effective distance tunnelled along z [2, 3]. This has pronounced effects on the tunnelling process. In particular, the intensity of the current resonances is modified with B and we relate these variations to the square of the Fourier transform, $|\Phi_{\text{QD}}(\mathbf{k})|^2$, of the electron probability density. The $G(B)$ plots provide a means of probing the characteristic form of the wavefunction probability density of the electron confined in the dot as a function of and hence of the corresponding spatial coordinate, y . Thus by plotting $G(B)$ for a *particular* direction of B we can measure the dependence of $|\Phi_{\text{QD}}(\mathbf{k})|^2$ along the \mathbf{k} -direction perpendicular to B . Then, by rotating B in the plane (X, Y) and making a series of measurements of $I(B)$ with \mathbf{B} set at regular intervals ($\Delta\theta \sim 5^\circ$) of the rotation angle θ , we obtain a full spatial profile of $|\Psi_{\text{QD}}(k_x, k_y)|^2$. This represents the projection in \mathbf{k} -space of the probability density of a given electronic state confined in the QD.

The model provides a simple explanation of the magnetic field dependence of the resonant current features “A”–“C”. In particular, the *forbidden* nature of the tunnelling transition

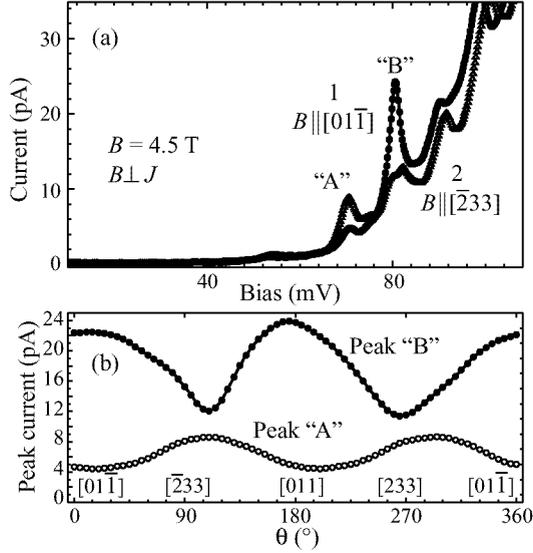


Fig. 3. (a) $I(V)$ characteristics in an in-plane magnetic field of 4.5 T. The first curve (circles) is for $B \parallel [01\bar{1}]$; the second curve (triangles) is for $B \parallel [\bar{2}33]$ (b) angular dependence of the peaks current.

associated with “B” (see Fig. 2(b)) at $B = 0$ T is due to the odd parity of the final state wavefunction, which corresponds to the first excited state of a QD. The applied magnetic field (i.e. the Lorentz force) effectively breaks the mirror symmetry at $B = 0$ and thus makes the transition *allowed*.

Figure 4 shows the spatial form of $G(B) \sim |\Psi_{\text{QD}}(k_x, k_y)|^2$, in the plane for the two representative QD states corresponding to the labelled features in Fig. 2. The k -values are estimated from relation (1), Δs assuming has nominal value of 63 nm consistent with the doping profile and composition of the device. The contour plots reveal clearly the characteristic form of the probability density distribution of a ground state orbital and the characteristic lobes of the higher energy states of the QD. The electron wavefunctions have

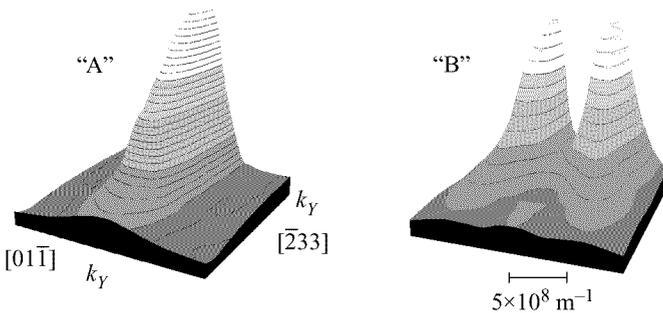


Fig. 4. Dependence of G on magnetic field for B parallel and antiparallel to $[01\bar{1}]$ for the different QDs states.

a biaxial symmetry in the growth plane, with axes corresponding quite closely (within measurement error of 15°) to the main crystallographic directions $X-$ and $Y-$ for (311)B-substrate orientation.

We have shown that magnetotunnelling spectroscopy provides us with a new means of probing the spatial form of the wavefunctions of electrons confined in zero-dimensional quantum dots. The technique exploits the effect of the classical Lorentz force on the motion of a tunnelling electron and can be regarded as the momentum \underline{k} -space analogue of STM imaging. The technique is both non-invasive and non-destructive and allows to spatial probe quantum states that are buried hundreds of nanometers below the surface.

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