Magnetotunnelling spectroscopy for probing the electron wave functions in self-assembled quantum dots


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Abstract

We show how resonant magnetotunnelling can provide a non-invasive and powerful method for mapping out the probability density of the quantum-confined states in self-assembled quantum dots. By measuring the magnetic field dependence of the intensity of the resonant tunnelling current through individual dots, we identify confined states in the dot displaying the elliptical symmetry of the ground state and the characteristic lobes of the higher energy states.

Keywords: Resonant tunnelling; Quantum dots; Electron wavefunctions

1. Introduction

Self-assembled quantum dots (QDs) are nanometre-sized clusters, which form spontaneously in strained semiconductor heterostructures and can confine the motion of an electron in all three spatial dimensions [1]. Although, it is relatively straightforward to measure the energy levels of QDs, it is much more difficult to obtain information about the form of the wave functions. In this paper, we use the technique of resonant magnetotunnelling spectroscopy (RMTS) to measure the probability density of the electronic states of InAs QDs.

There have been a number of experiments in which tunnelling spectroscopy was used to study transport through the zero-dimensional electronic states of individual InAs dots embedded in a single AlAs barrier [2–8]. In this work, we investigate resonant tunnelling in MBE-grown GaAs/(AlGa)As double-barrier resonant tunnelling diodes (RTDs) in which a single layer of InAs QDs is embedded in the centre of the GaAs quantum well (QW). These RTDs form a flexible “quantum laboratory” for investigating a variety of phenomena, including the dynamics of carrier tunnelling, capture and recombination through the QW [9]. Here, we show how RMTS can provide a non-invasive and powerful method for mapping out the probability density of the confined states in QDs.

2. Overview of magnetotunnelling spectroscopy

In a RMTS experiment, the application of a magnetic field, B, perpendicular to the tunnel current
introduces a change $\Delta k_\parallel$ in the momentum component of the tunnelling electron parallel to the tunnel barriers and perpendicular to $B$ [10]

$$h\Delta k_\parallel^2 = eB \Delta s,$$

(1)

where $\Delta s$ is the effective tunnelling distance. The formula can be understood in terms of the action of the Lorentz force on the tunnelling electron. An early application of this effect was to use the magnetic field to vary the $k$-vector of carriers tunnelling from extended emitter states into extended states in the QW. The applied voltage provides a means of tuning into the energy of a particular state in the QW; the applied field shifts the $k$-vector. The method proved an effective probe of the energy dispersion curves of quasi-1D skipping states [10] and bound states in QWs [11,12].

The RMTS technique was then extended to the case of tunnelling into a QW state of lower dimensionality: electrons confined in a quantum wire [13,14] (QWR) or by a donor in a QW [15]. In RMTS, the tunnel current is proportional to the modulus squared of the matrix element between the initial and final states of the tunnel transition. The $B$ dependence of the current can be expressed by the modulus squared of the overlap integral [13–15], represented in $k$-space as

$$I \sim \left| \int_{-\infty}^{+\infty} \varphi_e(k - \Delta k_\parallel) \varphi_e(k) \, dk \right|^2,$$

(2)

where $\varphi_e(k)$ and $\varphi_e(k)$ are the Fourier transforms of the real space wave function of the emitter state and the final state, respectively.

Eqs. (1) and (2) imply that $B$ can provide a means of measuring $\varphi_e(k)$ with a resolution in $k$-space given by the width of $\varphi_e(k)$. In particular, since the initial state in the emitter has only weak spatial confinement, $\varphi_e(k)$ corresponds to a sharply peaked function with a finite value only close to $k = 0$. Therefore, the intensity of the resonant current feature associated with the confined state is given approximately by $|\varphi_e(k)|^2$.

For the case of RMTS applied to the bound state of a donor in a QW [15], the bound electron is relatively weakly confined by the long range Coulomb confinement potential of the impurity, so that the applied $B$ was a strong perturbation on the localised state. In the experiment on the QWR, optical lithography and etching techniques were used to produce one-dimensional states in the well [13,14]. In this case, due to the stronger confinement potential, the magnetic field only weakly perturbed the confined states and the technique was able to determine the unperturbed form of the three lowest lying 1D states.

We now have extended the technique further to map out the electronic states of QDs, where there is strong confinement in all three spatial directions. The RMTS method may be regarded as complementary to scanning tunnelling microscopy (STM) and related techniques [16], which are powerful tools for imaging electronic states on or close to condensed matter surfaces. In that case, the moving tip acts as a probe of the wave function in real space. In RMTS, the magnetic field acts as a variable probe in $k$-space. An advantage of RMTS is that it can be used to probe states that are well away from the surface of a sample.

3. Samples

In our device, a layer of InAs QDs is embedded in the centre of an undoped 12-nm GaAs QW, which is sandwiched between two 8.3-nm Al$_{0.6}$Ga$_{0.6}$As tunnel barriers. The layer of QDs was grown by depositing 2.3 monolayers (ML) of InAs. The dots were grown on a (3 1 1)B- (sample qd311) or a (1 0 0)- (sample qd100) oriented GaAs substrate. Undoped GaAs spacer layers of width 50 nm separate the barriers from two contact layers with graded n-type doping. A schematic diagram of the device is shown in Fig. 1. The device acts as a RTD in which electrons can tunnel into the QD.
from a doped contact layer on the opposite side of the barrier. For comparison, we also studied a control sample grown with the same sequence of layers, but with no InAs layer (sample c).

4. Results and discussion

Fig. 2 shows the current–voltage characteristics, $I(V)$, for samples qd311 and c in negative bias (positive substrate). At low bias, they differ substantially: in the control sample we observed a single resonance due to electrons tunnelling through the first quasi-bound state of the QW; in contrast, in sample qd311, the current is strongly suppressed and a multitude of low-current resonant peaks can be observed.

The resonant current features observed in sample qd311 are related to the presence of the InAs QDs. In particular, for each feature, we observe a thermally-activated current onset, which is an unambiguous signature of an electron tunnelling from a thermalized Fermi-distribution of emitter states into an individual, discrete QD energy level [3,5]. The current amplitude is also consistent with electrons tunnelling one-at-a-time through a single state.

Note that the potential profile of the RTD with the dots is different from that of a RTD without dots. In the former case, at zero bias, equilibrium is established by electrons diffusing from the doped GaAs layers and filling the dot states. The resulting negative charge in the QW produces depletion layers in the regions beyond the (AlGa)As barriers, thus producing an effective tunnel barrier that is wider and higher than in the case of the control sample (see the inset of Fig. 2). The long tunnelling distance, $\Delta s$, is important in producing a large $k$ for a relatively modest $B$ (see Eq. (1)).

Here, we focus on the magnetic field dependence of the electron tunnelling through the QD states and on how this provides detailed information about the form of the wave function associated with an electron in a QD. Let $\theta$, $\beta$ and $Z$ indicate, respectively, the direction of $B$, the direction normal to $B$ in the growth plane $(X, Y)$, and the normal to the tunnel barrier, respectively (see Fig. 3). Eq. (1) then becomes

$$k_\beta = eB_\theta \Delta s/h.$$  \hfill (3)

Eqs. (2) and (3) imply that the magnetic field can provide a means of measuring $\varphi_{QD}(k)$ the wave function of a QD state. As before, the intensity of

\begin{align*}
I(V) \text{ characteristics at } 4.2 \text{ K for samples qd311 and c.} \\
\text{Inset: Sketch of the conduction band profile of the two samples under an applied bias.} \\
\text{Fig. 3. Schematic diagram of the RMTS experiment.} \theta, \beta \text{ and } Z \text{ indicate, respectively, the direction of } B, \text{ the direction normal to } B \text{ in the growth plane } (X, Y), \text{ and the normal to the tunnel barrier, respectively.}
\end{align*}
the resonant current feature associated with the QD state is given approximately by $|\varphi_{\text{QD}}(k)|^2$.

Fig. 4(a) shows the $I(V)$ characteristics at 4.2 K in reverse bias for sample qd311 in the presence of a magnetic field, $B$, applied at 30° from the [0 1 1] direction in the growth plane ($X$, $Y$). Three voltage regions are indicated, $i$, $ii$ and $iii$, corresponding to current features that show typical behaviour, as discussed below. All current resonances exhibit a strong dependence on $B$ and they all quench at high-magnetic fields. In particular, with increasing $B$, the low-voltage resonances (e.g., resonance $i$) decrease in amplitude, whereas the others (e.g., resonances $ii$ and $iii$) have a non-monotonic magnetic field dependence. For example, $ii$ is not visible at $B = 0$ T and develops with increasing field. All features also show a shift to lower voltage with increasing $B$, a consequence of the diamagnetic increase in the energy of the emitter states.

We can understand the magnetic field dependence of the resonances in terms of the effect of $B$ on a tunnelling electron. As discussed above, the $I(B)$ plot associated with a given current feature provides a means of measuring $|\varphi_{\text{QD}}(k_B)|^2$. This implies that the different magnetic field dependence of the current features $i$, $ii$ and $iii$ is because they arise from different types of dot state. In Fig. 4(b), we plot out the current variation of the three features as a function of the amplitude of $B$. The measured $|\varphi_{\text{QD}}(k_B)|^2$ are very similar to those for a harmonic oscillator, which are also shown for comparison in Fig. 4(b). Note that for the particular case of the simple harmonic oscillator, the $k$-space and real space wave functions have identical form.

By rotating the direction of $B$ in the plane of the tunnel barriers, our magnetotunnelling experiment can be used to derive full two-dimensional maps of the electron probability densities. By plotting $I(B)$ for a particular direction of $B$, we can measure the dependence of $|\varphi_{\text{QD}}(k_B)|^2$ along the $k$-direction perpendicular to $B$. Then, by making a series of measurements of $I(B)$ for various directions of $B$ in the growth plane ($X$, $Y$), we can obtain the full spatial profile of $|\varphi_{\text{QD}}(k_X, k_Y)|^2$. This represents the $k$-space projection of the probability density of the electronic state confined in the QD. Consistent with this model, we observed a pronounced dependence of the current intensity on the direction of $B$ in the growth plane ($X$, $Y$) (see the inset of Fig. 5).

Fig. 5 shows the spatial form of $|\varphi_{\text{QD}}(k_X, k_Y)|^2$ in the plane ($k_X, k_Y$) for two representative dot states for the (3 1 1)B and (1 0 0) QDs. 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 wave function has a biaxial symmetry in the growth plane, with axes corresponding closely to the main crystallographic axes ([0 1 1] and [2 3 3] axes for the (3 1 1)B, and [0 1 0] and [1 0 0] axes for the (1 0 0)).
Several different methods have been used to calculate the eigenstates of QDs, including perturbation effective mass approaches [1], 8-band $k \cdot p$ theory [17] and empirical pseudopotential models [18]. The wave functions are usually presented as plots of the probability density in real space, $|\varphi_{0d}(r)|^2$. A tunnel current measurement can provide no information about the phase of the wave function but, in general, the phase of $\varphi_{0d}(r)$ emerges naturally from the calculations. Once the phase factor is known, it is a straightforward task for theoreticians to Fourier transform the wave function into $k$-space. A direct comparison could then be made with our $I(B)$ plots.

To summarise, we have observed successive features in $I(V)$ corresponding to resonant tunnelling through a limited number of discrete states of self-assembled InAs QDs. The wave functions of these states display the symmetry of the ground state and first and second excited states of quantum dots. With the simple device configuration, we have used, it is not possible to tell whether or not an excited state and a ground state correspond to the same quantum dot. Also, despite the large number of quantum dots in our sample ($10^6$–$10^7$ for a 100 μm diameter mesa), we observed only a small number of resonant peaks over the bias range ($\sim 100$ mV) close to the threshold for current flow. Similar behaviour has been reported in earlier studies and is not fully understood [4,5]. This behaviour may be related to the properties of the electrons in the emitter: since the tunnelling probability for electron transmission through the dots is exponentially sensitive to the tunnelling distance, any disorder in the emitter contact may well enhance the current through adjacent dots.

5. Conclusion

We have studied the electron wave functions in InAs QDs incorporated in a $n-i-n$ GaAs/(AlGa)As double-barrier RTD. We have observed features in the low-temperature $I(V)$ characteristic of the diode, corresponding to carrier tunnelling into 0-dimensional states of individual dots. We probed the symmetry of the dot states using RMTS. This study revealed dot states displaying a biaxial symmetry in the growth plane. In particular, it reveals the elliptical symmetry of the ground state and the characteristic lobes of the higher energy states.

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References