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Resonant tunnelling through D^- states

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Abstract

We have studied tunnelling through Si donors incorporated in the quantum well of double barrier resonant tunnelling devices. In addition to a resonance associated with the ground state of a single donor (1s level), a novel donor-related resonance at a smaller binding energy is observed in high magnetic fields where it becomes dominant over the 1s resonance. We attribute this novel feature to a D^- state of a shallow donor.

Keywords: Many body and quasi-particle theories; Quantum wells; Tunneling

A shallow, hydrogenic atom which binds an extra electron is the simplest “many-body” electronic system. This system (D^- ion) has attracted significant interest, both theoretical and experimental, since the early days of quantum mechanics and is a basic test for our understanding of electron–electron interactions. The behaviour of D^- states becomes more prominent in a confined (quasi-2D) geometry and in strong magnetic fields, where research has focused in recent years [1,4]. So far, all experimental information about D^- states has come from optical measurements.

In this paper we report a novel donor-related resonance in tunnelling spectroscopy which is attributed to the D^- state. The resonance is

observed in double barrier resonant tunnelling devices (RTD) with intentional δ -doping by Si and appears in addition to a resonance due to tunnelling through the ground state (D^0 , 1s state) of the shallow donors [3]. The additional peak is clearly visible in high magnetic fields where its amplitude becomes significantly larger than the amplitude of the D^0 peak. The novel resonance cannot be explained by tunnelling via excited states of a shallow donor which are expected to yield a much smaller tunnel current and also to show a stronger field dependence of the peak position. The observed behaviour is in agreement with that expected from a D^- centre in high magnetic fields.

We have studied double-barrier RTD with δ -doping in the centre plane of the quantum well by Si donors with concentrations of 4×10^9 and 8×10^9 cm⁻². The thickness of both

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(Al_{0.4}Ga_{0.6})As barriers is 5.7 nm and the width of the quantum well is 9 nm. We also grew control devices without δ -doping. For the exact layer composition and experimental details we refer to Refs. [2] and [3].

Fig. 1 shows a schematic energy-band diagram of our devices under bias. A current flows when the energy of an electron in a two-dimensional electron gas (2DEG) formed at the emitter interface is resonant with a state in the quantum well. As the bias is increased, energy levels in the well pass through the resonant condition leading to a sequence of resonances in the $I(V)$ characteristics. The lowest 2D subband in the well gives rise to the main resonance. The δ -doping gives rise to an additional resonance at smaller biases which originates from tunnelling through the localised ground state (D^0) of shallow donors (see Fig. 2). This D^0 resonance has been studied earlier [2] and corresponds to electron flow via Si donors which switch between D^+ and D^0 states in the tunnelling process.

We focus below on a novel resonant feature which emerges at biases close to the onset of the main resonance when a strong magnetic field is applied. This resonance is shown in Fig. 2 where it is clearly seen in the first derivative of a typical $I(V)$ characteristic and is also visible as a weak shoulder on the $I(V)$ curve itself ($T=1.2$ K). The peak amplitude increases linearly with increasing Si concentration in the well and the peak is absent in the undoped devices indicating unambiguously

Fig. 1. Schematic energy-band diagram for our resonant tunneling devices (RTDs) under bias.

Fig. 2. $I(V)$ (upper curve) and its derivative (lower) for the $12\ \mu\text{m}$ square sample with a Si concentration of $4 \times 10^9\ \text{cm}^{-2}$ ($B=19$ T and $T=1.2$ K). The dashed curve shows the novel resonance after subtracting the main resonance contribution.

that the state is donor-related. The novel resonance has been observed in magnetic fields both parallel and perpendicular to the direction of the tunnel current. However, in the latter geometry resonant tunnelling is strongly field-dependent, making quantitative analysis more complicated. For brevity, we will discuss only the results for the parallel field orientation. Although the second donor-related resonance partially overlaps the onset of the main resonance, it can be traced in both $I(V)$ curves and their derivatives for all magnetic fields above 6 T. Furthermore, we can subtract the background current due to the onset of the main resonance using $I(V)$ characteristics obtained on the undoped devices in the same magnetic fields. The dashed curve in Fig. 2 shows an example of the resulting resonance after such a subtraction. We emphasise that the essential behaviour of the donor resonance is not sensitive to details of the subtraction procedure and therefore we can employ it for comparison between the experiment and a theory.

Fig. 3 plots peak positions and amplitudes of both donor resonances as a function of magnetic field for two samples with different doping concentrations. Also, two solid curves are shown that are measured at a constant current corresponding to the onset of the D^0 and the new resonances. These curves demonstrate that the onset of the donor resonance behaves somewhat differently from the peak. With increasing magnetic field the D^0 resonance exhibits a shift to lower biases which corres-

Fig. 3. (a) Peak positions and (b) amplitudes of D^0 (open symbols) and D^- (filled) resonances. ($\bullet$) is for δ -doping $4 \times 10^9 \text{ cm}^{-2}$ and ($\circ$) for $8 \times 10^9 \text{ cm}^{-2}$. The two solid curves are measured at constant currents $I = 0.1$ and $0.9 \mu\text{A}$ for the sample with a δ -doping of $4 \times 10^9 \text{ cm}^{-2}$ indicating the onset of the two donor resonances.

ponds to a significant increase in its binding energy and indicates that this state is strongly localised [2]. In contrast, the second donor resonance is only weakly field dependent. In fields above 6 T its peak position stays virtually constant while its onset shifts slowly to lower biases (i.e. the resonance broadens). Note that the position of the main resonance is essentially field independent for this field direction [2]. As the magnetic field increases, the amplitude of the second donor resonance first increases and then saturates at higher fields while the 1s resonance decays monotonically.

At 20 T, the novel peak becomes nearly 10 times stronger than the D^0 resonance. The bias position, weak field dependence and relatively large amplitude of the novel resonance, all indicate a large spatial extent of the corresponding donor state.

The observed weakly bound level may be due to either excited states of a donor or a more complicated, many-body state such as D^- . To distinguish between these two possibilities we have calculated the binding energies and tunnelling probabilities for states bound to the lowest Landau level in our structures following the procedure discussed in Ref. [4]. The main results are shown in Fig. 4 which plots the field dependence of the binding energies for 1s, $2p^-$, $3d^-$ and D^- levels. The experimental data are presented by circles. A factor of 0.27 to the electrostatic leverage [3] has been used to convert the applied bias into energy. In the high field limit, the field dependence of the D^0 peak is in excellent agreement with our calculations for the 1s state. As far as the second donor-related peak is concerned, only the D^- level gives a reasonable fit for both the absolute value of the binding energy and its field dependence (see Fig. 4). Note that the accuracy of our data for the field dependence of the D^- resonance is limited by its broadening in high fields. The measured peak position of the D^- is nearly field independent while the onset of the resonance (plotted in Fig. 3) exhibits the expected increase in the binding energy for $B \gtrsim 6 \text{ T}$ (Fig. 4). In low fields, there is generally no

Fig. 4. Binding energy of donor states bound to the lowest Landau level in a 9 nm quantum well.

agreement between the calculated and experimental dependences for the both donor-related resonances. However, we note that some of the non-monotonic behaviour observed in low magnetic fields is probably related to the transition of the emitter 2DEG into the quantum limit ($\nu=1$ at $B \approx 6$ T).

Another major argument against the interpretation of the second resonance in terms of excited levels of a single donor comes from comparison of the tunnelling probabilities for the ground $1s$ and excited $2p^-$, $3d^{-2}$, $4f^{-3}$ states. In high magnetic fields ($\nu \lesssim 1$), we have found that the overlap integral for tunnelling between the first Landau level and the $1s$ state is respectively 6 and 30 times larger than for the $2p^-$ and $3d^{-2}$ states. The overlap decays rapidly for higher excited states. This infers that tunnelling via the excited states is too weak to account for the strong new resonance. On the other hand, the calculated overlap for D^- is nearly twice as large as that for the $1s$ state in the fields between 15 and 20 T and the high-field behaviour of the second donor-related resonance is in agreement with tunnelling through the D^- state.

The D^- resonance requires the presence of neutral donors in the quantum well since D^0 is the initial state in this tunnelling process. Such neutral donors may appear only due to inelastic tunnelling of 2D electrons since, at biases corresponding to the D^- peak, the $1s$ state is below the bottom of the 2DEG and, hence, out of resonance. The inelastic tunnelling can occur with emission of plasmons in the 2DEG. Furthermore, we expect that a D^- centre in the quantum well does not

emit its electrons directly into the collector contact but first lets one of them hop to the nearest positively charged Si atom in the well. The latter process has a much smaller tunnel barrier. This dissociation of D^- into two neutral donors is likely to give rise to a large concentration of neutral donors available for the D^- process and could explain the rather large amplitude of the D^- peak.

In conclusion, we have found a new strong tunnel resonance through a shallow donor in the quantum well whose behaviour in high magnetic fields is consistent with tunnelling via a D^- centre. Its large amplitude as well as a complicated behaviour in low magnetic fields ($\nu \lesssim 1$) remain to be explained.

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