D^- centers probed by resonant tunneling spectroscopy

J. G. S. Lok, A. K. Geim, and J. C. Maan

High Field Magnet Laboratory, Research Institute for Materials, University of Nijmegen, 6500 GL Nijmegen, The Netherlands

I. Marmorkos and F. M. Peeters

Department of Physics, University of Antwerp, B-2610 Antwerp, Belgium

N. Mori, L. Eaves, T. J. Foster, P. C. Main, J. W. Sakai, and M. Henini

Department of Physics, University of Nottingham, Nottingham NG7 2RD, United Kingdom

A donor-related resonance is observed in double-barrier resonant tunneling devices with Si donors incorporated in the quantum well. In high magnetic fields the resonance becomes dominant over the $1s$ resonance associated with the ground state of a single donor. The bias position of the donor resonance, its magnetic field dependence, and large amplitude indicate unambiguously that the resonance is due to tunneling through the ground state of a shallow donor with two bound electrons (D^- level).

A shallow, hydrogenic atom which binds an extra electron is the simplest ''many-body'' electronic system. This system (D^- ion) is a basic test for our understanding of many-body phenomena and has attracted significant interest, both theoretical and experimental, since the early days of quantum mechanics. The behavior of D^- states becomes most prominent in a confined [quasi-two-dimensional (2D)] geometry and in strong magnetic fields where research has focused in recent years.[1–6] So far, all experimental information about D^- states has come from optical measurements.

In this paper we report an observation of the D^- state in tunneling spectroscopy. A donor-related resonance has been found in double-barrier resonant tunneling devices (RTD) with intentional δ doping by Si in the center plane of the quantum well. This resonance appears in addition to the known resonance due to tunneling through the ground state (D^0, $1s$ state) of the shallow donors.[7] 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 tunneling via excited states of a shallow donor which are expected to yield a much smaller tunnel current and also a stronger field dependence of the binding energy. The observed behavior is in agreement with that expected from a D^- center in high magnetic fields.

There are two important aspects in the observation of D^- centers in a tunneling experiment. First, tunneling spectroscopy gives directly the binding energy of the donor state and this information is complementary to that obtained in an optical experiment where transition energies between the ground and excited states are measured. Second, there is much current interest in studying tunneling through a single isolated impurity.[8–13] Shallow donors in RTD have been found to give rise to resonant features due to not only the $1s$ level but also ''donor molecule'' levels and donor states coupled with random potential fluctuations.[9] The evidence for a strong D^- resonance is important for further understanding of the impurity related structure in resonant tunneling devices.

We have studied double-barrier RTD with δ doping in the center plane of the quantum well by Si donors with concentrations of 4×10^9 and 8×10^9 cm^{-2}. The thickness of both $(\text{Al}_{0.4}\text{Ga}_{0.6})$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. 7–9.

The inset in 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 tunneling through the localized ground state (D^0) of shallow donors (see the inset).
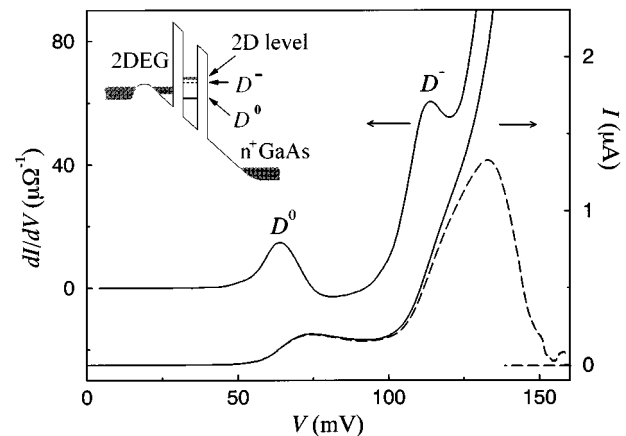

FIG. 1. $I(V)$ and its derivative near the onset of the main resonance for the sample 12 μm square with Si concentration 4×10^9 cm^{-2} ($B=19$ T and $T=1.2$ K). The dashed curve shows the resonance after subtracting the main resonance contribution. The inset is a schematic energy-band diagram for our RTD's under bias.
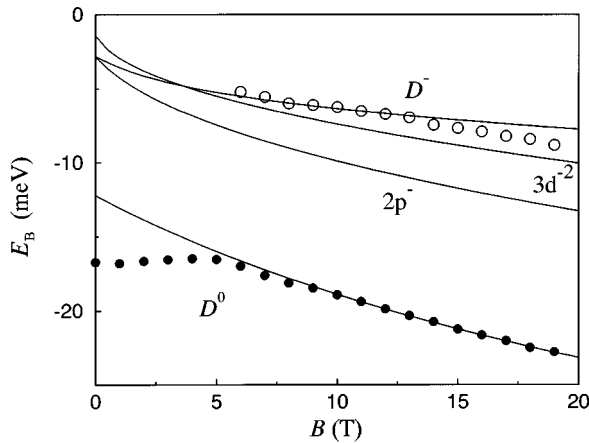
FIG. 2. Binding energy of donor states bound to the lowest Landau level in a 9-nm quantum well. Symbols are experimental data; solid lines are theory.

FIG. 3. Amplitudes of the D^0 (squares) and D^- (circles) resonances. Open symbols are for δ doping 4×10^9 cm^{-2}, filled symbols for 8×10^9 cm^{-2}. Solid curves are calculated amplitudes for various energy levels of a shallow donor in the quantum well of 9 nm width.

This D^0 resonance has been studied earlier[7] and corresponds to electron flow via Si donors which switch between D^+ and D^0 states in the tunneling process.

We focus below on a resonant feature which emerges at biases close to the onset of the main resonance if a strong magnetic field is applied. This resonance is shown in Fig. 1 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; $B=19$ T). The peak amplitude increases linearly with increasing Si concentration in the well and the peak is absent in the undoped devices indicating unambiguously that the state is donor related. In low fields the resonance overlaps strongly the onset of the main resonance, but we are able to trace the feature in both $I(V)$ curves and their derivatives for magnetic fields down to 3 T. However, a reliable quantitative analysis of the experimental data appears to be possible only for fields above 6 T.[14] The novel donor resonance has been observed in magnetic fields both parallel and perpendicular to the direction of the tunnel current. In the latter geometry the current is strongly field dependent, and this makes analysis more complicated (see, e.g., Ref. 7). For brevity, we discuss only the results for the parallel field orientation.

Figure 2 plots the binding energies for both donor resonances as obtained from the position of the maximum in the derivative curves (e.g., see Ref. 7). A leverage factor α which relates the applied voltage to the energy is found experimentally from the Landau level structure at biases above the main resonance, and, independently, from temperature dependence of the tunnel current through a single impurity.[7,8] Its value $\alpha \approx 0.3$ is in good agreement with modeling of the voltage distribution in our devices. With increasing magnetic field the binding energy of the D^0 resonance increases significantly (see Fig. 2) in agreement with the fact that this state is strongly localized.[7-9] The second donor resonance exhibits a somewhat weaker field dependence. To avoid confusion, we note that the binding energy is counted with respect to the free electron level in the quantum well, and the position of the main (free electron) resonance is essentially field independent for the discussed field direction.
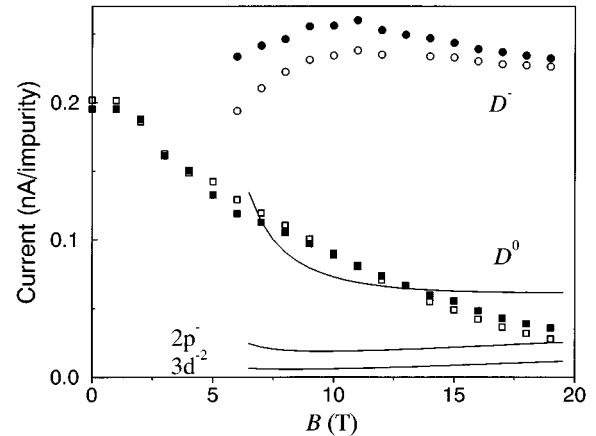
We have also analyzed the field dependence of the amplitude of the donor resonances. The results are plotted in Fig. 3 for devices with donor concentrations of 4 and 8×10^9 cm^{-2}. For quantitative analysis of the D^- amplitude, we have to subtract the background current due to the onset of the main resonance. This is done by using a simple exponential curve which fits $I(V)$ characteristics of the undoped devices at these biases. The dashed curve in Fig. 1 shows the resulting resonance on the $I(V)$ curve. We emphasize that the essential behavior in Fig. 3 is not sensitive to details of the subtraction procedure. It is seen in Fig. 3 that, with increasing magnetic field the amplitude of the second donor resonance first increases and then decreases slightly at higher fields while the $1s$ resonance decays monotonically and more rapidly. Note that at 19 T the peak becomes nearly ten times stronger than the D^0 resonance.

The bias position, the weak field dependence, and the large amplitude of the resonance all indicate a large spatial extent of the corresponding donor state. Such a 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 for states bound to the lowest Landau level in the quantum well following the procedure discussed in detail in Ref. 4. The results are shown in Fig. 2.

Figure 2 plots the field dependence of the binding energies for $1s$, $2p^-$, $3d^{-2}$, and D^- levels. In the high-field limit, the field dependence of the D^0 peak is in excellent agreement with our calculations for the $1s$ state. However, in low fields the calculated and experimental dependences differ considerably with a clear change in the slope of the experimental curve at about 6 T. The change is clearly associated with the transition of the emitter 2DEG into the quantum limit ($\nu=1$ at $B \approx 6$ T), where only the lowest Landau level is occupied. The low-field behavior is not important for our present discussion and will be considered elsewhere.

As far as the second donor-related peak is concerned,

among excited states the lowest one ($2p^-$) is expected to dominate in tunneling (see below). Figure 2 shows clearly that the $2p^-$ has a considerably larger binding energy and cannot be responsible for the new peak. On the other hand, the D^- level gives a good fit for *both* the absolute value of the binding energy and its field dependence (Fig. 2). We note that the accuracy of our data for the field dependence of the second donor resonance is limited by its broadening in high fields and the deviations from the theoretical curve for D^- in Fig. 2 are within the accuracy of the experiment. The broadening may be due to various donor positions in the well which yield different field dependences for the corresponding D^- states.[6]

Another major argument against the interpretation of the donor resonance in terms of excited levels of a single donor comes from the comparison of absolute values of the tunneling probabilities for the ground $1s$ and excited $2p^-$ and $3d^{-2}$ states. In high magnetic fields ($\nu < 1$), we have found that the square of the overlap integral for tunneling between the first Landau level and the $1s$ state is about 3 and 7 times larger than for the $2p^-$ and $3d^{-2}$ states, respectively. The overlap decays rapidly for higher excited states. The smaller matrix elements can be easily understood as the initial state in the emitter has a wave function with a single maximum, while wave functions of the excited states are oscillating. The higher the excited level number the more rapid the oscillations. The tunnel current depends also on the number of D^+ states in the quantum well available for the tunnel process. This number does not depend on whether it is the ground state or an excited level and, therefore, the difference in the tunneling probabilities leads directly to the same difference in tunnel currents. The large amplitude of the novel resonance indicates that it cannot be due to tunneling via excited states which are expected to give small resonant peaks not resolved in our experiment.

Moreover, these peaks are likely to overlap each other giving rise to an impurity band which extends from the $2p$ level up to the 2D subband and, therefore, is not distinguished from the main resonance.

Figure 3 compares the calculated and experimental field dependences for the resonant current through different single-electron donor states. In the calculations, we have considered tunneling as a scattering problem[15] where a free electron at the lowest Landau level in the emitter is scattered into the corresponding donor state in the well by the attractive donor potential. Screening of the donor charge by the 2DEG is taken into account using the Thomas-Fermi approximation. The overall value of the tunnel current is used as a single fitting parameter. Figure 3 indicates that the current through excited states remains small in the whole magnetic field interval. There is no detailed agreement between the experiment and theory for the field dependence of the tunnel current, even for the simplest case of D^0. Further analysis is required and we speculate that it may be necessary to take into account a strong local perturbation of the initial tunnel state in the emitter 2DEG by the positive donor charge.[8]

Finally, we note that the strong D^- resonance requires the presence of a considerable number of neutral donors in the quantum well as D^0 is the initial state in this tunneling process. Such neutral donors may appear due to inelastic tunneling of 2D electrons into the well[16] but the dominant process is likely to be the ''dissociation'' of D^- into two neutral donors ($D^- + D^+ \rightarrow 2D^0$). In such a process one of D^- electrons hops or tunnels onto the nearest positively charged Si atom in the well. This process has a much smaller barrier than the direct tunneling of a D^- electron into the collector contact. Therefore, we expect that there are few positively charged donors left in the well at biases corresponding to the D^- resonance. This means that the number of initial states (D^0) for the case of D^- resonance can be expected to be about the same as the number of D^+ at the D^0 resonance.

In conclusion, we have found a strong tunnel resonance through a shallow donor in the quantum well whose behavior is consistent with tunneling via a D^- center.

[1] S. Huant, S. P. Najda, and B. Etienne, Phys. Rev. Lett. **65**, 1486 (1990); S. Huant, A. Mandray, J. Zhu, S. G. Louie, T. Pang, and B. Etienne, Phys. Rev. B **48**, 2370 (1993).

[2] S. Holmes, J. P. Cheng, B. D. McCombe, and W. Shaff, Phys. Rev. Lett. **69**, 2571 (1992); J. P. Cheng, S. Holmes, Y. J. Wang, B. D. McCombe, and W. Schaff, Physica B **184**, 409 (1993).

[3] E. R. Mueller, D. M. Larsen, J. Waldman, and W. D. Goodhue, Phys. Rev. Lett. **68**, 2204 (1992); H. L. Fox and D. M. Larsen, Phys. Rev. B **51**, 10 709 (1995).

[4] J. M. Shi, F. M. Peeters, and J. T. Devreese, Phys. Rev. B **51**, 7714 (1995), and references therein.

[5] T. Pang and S. G. Louie, Phys. Rev. Lett. **65**, 1635 (1990); X. Xia and J. J. Quinn, Phys. Rev. B **46**, 12 530 (1992); A. B. Dzyubenko, Phys. Lett. A **173**, 311 (1993).

[6] J. L. Zhu and S. Xu, J. Phys. Condens. Matter **6**, L299 (1994); J. Blinovski and T. Szwacka, Phys. Rev. B **49**, 10 231 (1994).

[7] J. W. Sakai, T. M. Fromhold, P. H. Beton, M. Henini, L. Eaves, P. C. Main, F. W. Sheard, and G. Hill, Physica B **184**, 241 (1993); Phys. Rev. B **48**, 5664 (1993), and references therein.

[8] P. J. McDonnell, A. K. Geim, P. C. Main, T. J. Foster, P. H. Beton, and L. Eaves, Physica B **211**, 433 (1995); A. K. Geim, P. C. Main, N. La Scala, Jr., L. Eaves, T. J. Foster, P. H. Beton, J. W. Sakai, F. W. Sheard, M. Henini, G. Hill, and M. A. Pate, Phys. Rev. Lett. **72**, 2061 (1994).

[9] A. K. Geim, T. J. Foster, A. Nogaret, N. Mori, P. J. McDonnell, N. La Scala, Jr., P. C. Main, and L. Eaves, Phys. Rev. B **50**, 8074 (1994).

[10] B. Su, V. J. Goldman, and J. E. Cunningham, Science **255**, 313 (1992); Phys. Rev. B **46**, 7644 (1992).

[11] M. R. Deshpande, E. S. Hornbeck, P. Kozodoy, N. H. Dekker, J. W. Sleight, M. A. Reed, C. L. Fernando, and W. R. Fresley, Semicond. Sci. Technol. **9**, 1919 (1994).

[12] U. Sivan, F. P. Milliken, K. Milkove, S. Rishton, Y. Lee, J. M. Hong, V. Boegli, D. Kern, and M. DeFranza, Europhys. Lett. **25**, 605 (1994).

[13] A. K. Savchenko, V. V. Kuznetsov, A. Woolfe, D. R. Mace, M. Pepper, D. A. Ritchie, and G. A. C. Jones, Phys. Rev. B **52**, 17 021 (1995).

[14] These fields correspond to the quantum limit $\nu < 1$ when only the lowest Landau level is occupied in the emitter 2DEG. The period of Shubnikov–de Haas–like oscillations in the tunnel cur-rent yields $\nu = 1$ at $B \approx 6$ T.

[15] A. I. Larkin and K. A. Matveev, Zh. Eksp. Teor. Fiz. **93**, 1030 (1987) [Sov. Phys. JETP **66**, 580 (1987)].

[16] At biases corresponding to the D^- peak, the $1s$ state is below the bottom of the 2DEG and, hence, out of resonance. However, inelastic processes are important in our devices and give a long tail of a nonresonant current. Such a tail can be most clearly seen in $I(V)$ characteristics of a single impurity where it is not obscured by the onset of the main resonance.