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Resonant tunnelling via states of the X-related donors located at different atomic layer in AlAs barrier

Yu. N. Khanin, E. E. Vdovin and Yu. V. Dubrovskii
Institute of Microelectronics Technology and High Purity Material, Russian Academy of Sciences, Chernogolovka, Moscow District, 142432 Russia

Abstract. We report an electrical transport and magnetotransport study of GaAs/AlAs/GaAs single-barrier heterostructures incorporating unintentional donors in the barrier. Resonant tunnelling was observed both through the quasiconfined states in the AlAs layer originated from the X_{XY} and X_Z conduction band minima and through two distinct states of the donors bound to the X_{XY} and X_Z valleys. Furthermore we observed an additional oscillatory like fine structure of the donor resonances that we attribute to difference in binding energies of donors located at different position of the AlAs layer. Magnetic field behaviour of the fine structure demonstrated that the binding energy of X-related donors has an essential dependence on both magnetic field and donor position in the barrier.

Recent investigations of AlAs/GaAs heterostructures have demonstrated that X-valley states in AlAs have a substantial influence on their optical and electrical properties [1, 2]. For silicon donors in bulk AlAs, the central cell potential does not mix the three hydrogenic effective-mass states and its thus can be described as corresponding to independent X valleys. Therefore, the ground state of a silicon donor is threefold degenerated. However, in a thin AlAs layer this degeneracy is lifted due to confinement and strain, so that threefold degenerated state splits into a two-fold degenerate state associated with X_{XY} valleys and a non-degenerate state associated with X_Z valley [1]. The binding energies of hydrogeniclike donors bound to the X_{XY} and X_Z valleys were calculated by Gerald Weber, with both the mass anisotropy and the quantum confinement taken into account [3]. Moreover was shownthat the binding energy of the donor depends on it position in the AlAs layer and donor resonances should occur at a different voltages for impurities located at different distances from the heterointerface. Tunnelling spectroscopy allows to measure directly the donor binding energy provided that resonanses corresponding to tunnelling via both the confined state and the donor state associated with them is observed. In our previous paper we have reported the detection of two X_{XY} and X_Z-related donor resonances [4] (see Figure 1).

In this paper we report the first observation an additional oscillatory like fine structure of the donor resonances that we attribute to difference in binding energies of donors located at different position of the AlAs layer. Study of the behaviour of the fine structure with magnetic field demonstrate that the binding energy of X related donors has an essential dependence on both magnetic field and donor position in the barrier in agreement with earlier theoretical results [3, 5].

The sample studied was a single-barrier GaAs-AlAs-GaAs heterodiode, grown by molecular-beam epitaxy on (100)-oriented Si doped n-GaAs substrate. The AlAs layer was not intentionally doped but the donor impurities were present in AlAs because of diffusion from the highly doped region during the growth. Figure 2(a) displays the additional oscillatory like fine structure of the X_{XY}-related donor resonance at magnetic fields from 12.75 to 14 T and $T = 0.4$ K. Note that the fine structure exists in the absence of the magnetic

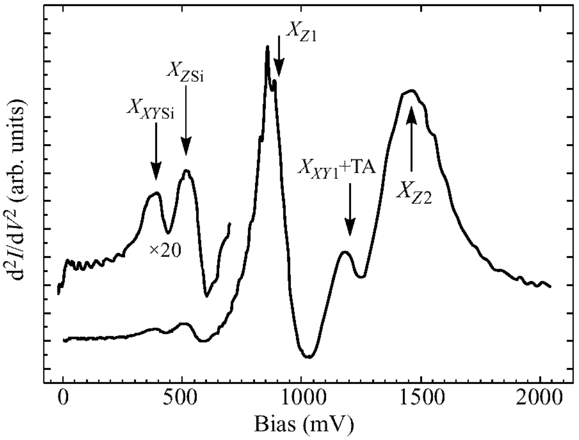

Fig. 1. The second derivative characteristic of the experimental device at 4.2 K. The calculated threshold voltages are denoted by arrows. Two lowest quasiconfined states in the X quantum well and two states of the donors linked to them are denoted by X_{XY1}, X_{Z1} and X_{XY} Si, X_Z Si.

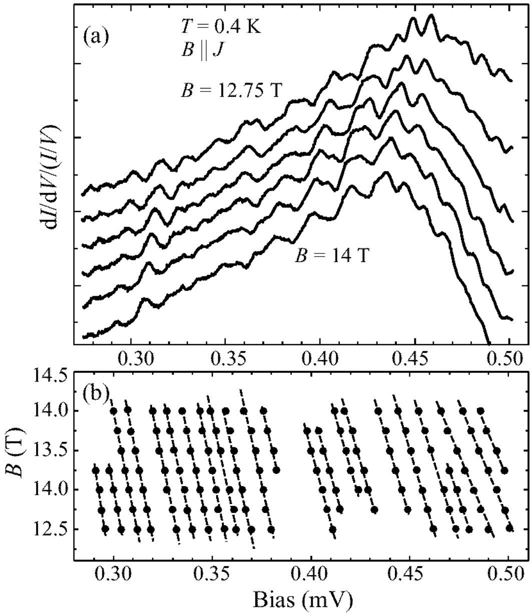

Fig. 2. (a) Normalised conductance-voltage curves for magnetic fields from 12.75 to 14 T at $T = 0.4$ K. The curves are vertically offset for clarity. (b) Fan diagram of the fine structure peak positions as function of the magnetic field.

field and intensifies with increasing magnetic field. However the conductance curve shows complex changes with the magnetic field which are partly due to Landau level quantization in the emitter and partly due to the fine structure. Therefore we studied the fine structure in a strong magnetic field when Landau level quantization leads only to monotonic moving of the resonant peaks. The structure appears to be sample specific but is exactly reproducible for a given sample even after thermal recycling. The medium period of this structure is about 15 mV that corresponds to an energy separation by approximately 1.2 meV. When the temperature was increased up to 20 K ($kT \approx 1.25$ meV) the fine structure disappeared completely due to the thermal broadening. Resonant tunnelling via individual states of the donors located at different atomic layer leads only to an additional fine structure of the main impurity resonances [3]. On the other hand, the fine structure of resonances in devices with large lateral dimensions can be caused by interface roughness [6]. However, the binding energy of donor has stronger dependence on its position in the barrier than on the width of the barrier itself. When the thickness of the 5 nm AlAs barrier varies on 2 monolayers (it's a typically value of MBE technology interface roughness) the binding energies of the central X_Z and X_{XY} related donors varies on 2 and 4 meV respectively. The difference in binding energies of donors located at the center of the 5 nm AlAs barrier and at the heterointerface is 30 meV and 20 meV for X_Z and X_{XY} related donors respectively [10]. Thus we consider that in our experimental situation the fine structure is related to the random distribution of the donors in the barrier. In a magnetic field applied along the direction of the current, the fine structure shows a shift to lower bias with increasing field. The fan diagram of the observed peak position as a function of the magnetic field is shown in Fig. 2(b). Fine structure peaks in the voltage range from 300 to 500 mV near X_{XY}-related donor resonance move to lower bias as the magnetic field increases at a rate from 8 to 20 mV/T respectively and the rate is a monotonic increasing function of the voltage (see Fig. 2(b)). It should be noted that Landau quantization leads to equal voltage shift of the resonant peaks. On the other hand, our self-consistent Poisson-Schrodinger calculations show that over the bias range of interest (300–500 mV) the ratio of the total voltage drop in the structure to that in the barrier region (leverage factor) varies slightly from 12 to 12.7. Therefore we consider that the significant difference in shift rates of the peaks is due to binding energy of the more spread out state of the donor located at the heterointerface has a stronger dependence on magnetic field then that of the more localised state of the donor located at the centre of the barrier [3, 5]. In other words behaviour of the fine structure with magnetic field is the experimental verification of the significant dependence of the binding energies of X-related donors on its position in barrier that has been predicted theoretically [3].

To summarise we have reported a transport study of tunnelling through indirect-gap GaAs/AlAs/GaAs single-barrier structure. We have observed an additional oscillatory like fine structure of the donor resonances that we attribute to difference in binding energies of donors located at different position of the AlAs layer. Study of the behaviour of the fine structure with magnetic field demonstrated that the binding energy of X-related donors has an essential dependence on magnetic field and donor position in the barrier in agreement with earlier theoretical results [3, 5].

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References

[1] H. W. van Kesteren, E. C. Cosman, P. Dawson *et al.*, *Phys. Rev. B* **39**, 13426 (1989).
[2] R. Teissier, J. J. Finley, M. S. Skholnic *et al.*, *Phys. Rev. B* **54**, 8329 (1996).
[3] Gerald Weber, *Appl. Phys. Lett.* **67**(10), 1447 (1995).
[4] Yu. N. Khanin, K. S. Novoselov and E. E. Vdovin, *Fiz. Tekh. Poluprovod.* **35**(2), 206 (2001).
[5] J. M. Shi, F. M. Peeters, G. Q. Hai and J. T. Devreese, *Phys. Rev. B* **44**, 5692 (1991).
[6] Y. C. Kang, M. Suhara, K. Furuya *et al.*, *Jpn. J. Appl. Phys.***34** Pt.1 , 4417 (1995).