AIP | Applied Physics Letters

Characterization of resonant tunneling paths in current–voltage characteristics line shapes

P. H. Rivera and P. A. Schulz

Citation: Applied Physics Letters **67**, 2675 (1995); doi: 10.1063/1.114289
View online: http://dx.doi.org/10.1063/1.114289
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/67/18?ver=pdfcov
Published by the AIP Publishing

Characterization of resonant tunneling paths in current–voltage characteristics line shapes

P. H. Rivera and P. A. Schulz
Instituto de Física Gleb Wathagin, Universidade Estadual de Campinas, 13083-970 Campinas, SP, Brazil

(Received 7 February 1995; accepted for publication 22 August 1995)

We analyze the current density-voltage characteristics of double-barrier tunneling diodes, with different spacer layers, within the framework of a Poisson solver together with a coherent tunneling approximation for transmission probabilities. We show that varying the spacer layer thickness, together with barrier heights, changes dramatically the current density-voltage characteristics line shape, which is revealed to be an important qualitative signature of the tunneling paths involved in the double-barrier diodes under operation. © *1995 American Institute of Physics.*

Resonant tunneling double-barrier diodes GaAs/AlGaAs have received attention since the observation of spatial confinement effects on their current–voltage characteristics.[1] Spacer layers between the heavily doped contacts and barriers have been used in order to get higher peak currents and greater peak-to-valley ratios.[2] These efforts were followed by numerical calculations for the current density-voltage characteristics.[3] The main challenge to these calculations is properly taking into account the scattering mechanisms together with the dynamical aspects of charge redistribution during current flow.[4] Due to the complexity of the problem, the use of simple "Poisson solvers" became widespread as support to experimental work.[5] These Poisson solvers are normally based on the semiclassical Thomas–Fermi approximation, neglecting the confinement effects in the accumulation layers. Recently, Fiig and Jauho[6] (FJ) proposed a hybrid model: a semiclassical approximation for bulk (3D) electrons in the contacts with a more appropriate treatment of the electrons in the accumulation layer. Nevertheless, systematic investigation of the consequences of varying the spacer layer thicknesses are not common in the literature.[7] With the presence of spacer layers one has the formation of accumulation layers with quantized levels leading to an additional two-dimensional (2D) electronic system, coupled to the double-barrier structure. It turns out that the tuning of the 2D electron gas at the accumulation layer leads to dramatic changes in the line shape of the current–voltage characteristics as a function of device parameters. The main result is that one has two clear limits for the line shape of the current–voltage characteristics, involving a single quasibound state in a double-barrier quantum well: single asymmetric and doubly peaked I–V curves.

We consider $Al_xGa_{1-x}As$–GaAs symmetric double-barrier structures with symmetric spacer layers. Our Poisson solver is based on the FJ model, where the electron concentration outside the double-barrier structure is given by

$$n(z)=N_c\mathscr{F}_{1/2}\left(\frac{\mu-E_c(z)}{kT}\right)+\sum_i kT\left(\frac{m^*}{\pi\hbar^2}\right)\times\ln(1+e^{(\mu-\epsilon_i)/kT})|\Psi_i|^2, \quad (1)$$

where $\mathscr{F}_{1/2}$ is the jth order Fermi–Dirac integral, $E_c(z)$ is the profile of the conduction band minimum to the left of the maximum of the potential bump in the spacer layer region. To the right of this point, $E_c(z)$ is kept fixed at this maximum value. ϵ_i and Ψ_i are the energy and the wave function of the ith bound state in the accumulation layer. In the double-barrier quantum well, the electron concentration is given by the second term of Eq. (1), with the probability density weighted by a factor,[8] $T_e/(T_e+T_c)$, where $T_e(T_c)$ is the transmission probability through the emitter (collector) barrier.

In what follows we have a contact doping of $n^+=10^{18}\ \text{cm}^{-3}$, barrier and well thicknesses of 25 and 50 Å, respectively. Al concentration ranges from $x=0.3$ to $x=0.57$; $\Delta E_c=258$ meV–$\Delta E_c=507$ meV at the Γ point.[9] Tunneling through X states in the collector barrier can be neglected for the bias range investigated here. Figure 1 shows the potential profile for a double barrier structure under applied bias. We notice the formation of the potential bump in the spacer layer region. By increasing the spacer layer thickness, the accumulation layer is progressively isolated from the emitter contact region. Having Fig. 1 in mind, one could identify three possible coherent tunneling paths through the quasibound states in the double-barrier well: (i) tunneling of 3D electrons directly from the remote emitter, over the potential bump; (ii) tunneling of 3D electrons through quasi-2D states, first in the

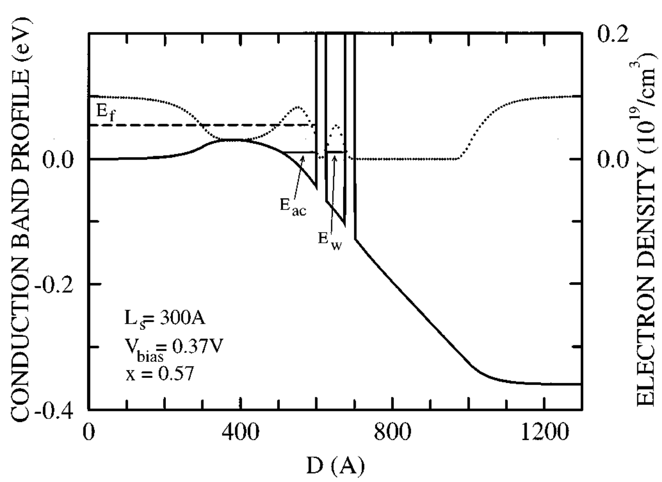

FIG. 1. Profile of the conduction band minimum and electronic density (dotted line) for a double barrier structure under applied bias. The quasibound states in the accumulation layer and the double barrier quantum well are also shown.

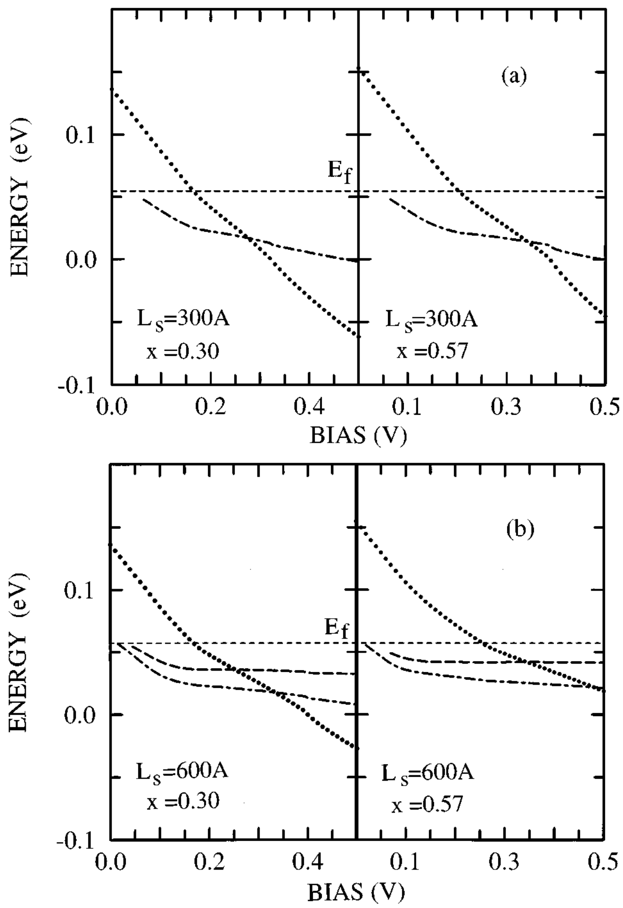

FIG. 2. Position of the energy levels of a double barrier structure as a function of applied bias. Left (right) panels are for lower (higher), $x=0.3$ ($x=0.57$), Al concentration in the barriers. The spacer layers thicknesses are (a) $L_s=300$ Å and (b) $L_s=600$ Å. Dotted lines are for the level in the double barrier and dot–dashed and long dashed lines are for states in the accumulation layers. Other structure parameters are given in the text. The dashed lines indicate the position of the Fermi energy in the emitters.

accumulation layer and then in the double barrier; (iii) tunneling directly from a 2D state in the accumulation layer lying below the conduction band minimum of the remote 3D emitter. Which of these cases contribute to the tunneling process can be verified by showing the positions in energy of the quasi-2D states as a function of applied bias for a given structure. This is illustrated in Fig. 2, where the spacer layer thickness is changed from (a), $L_s=300$ Å to (b), $L_s=600$ Å, considering $x=0.3$ and $x=0.57$ for both cases. In Fig. 2 we observe anticrossings between quasibound states of the quantum well and accumulation layer. These anticrossings occur at energies above the conduction band minimum at the remote 3D emitter contact at the far left (see also Fig. 1). Current density–voltage (J–V) characteristics including these anticrossings effects can therefore be evaluated by means of the Esaki–Tsu equation.[10] The transmission probability is calculated by considering a plane wave incident from the far left and integrating the Schrödinger equation[11] in the effective-mass approximation for a potential profile given by the solution of the Poisson solver.

In Fig. 3, J–V characteristics for double-barrier diodes with spacer layers 300 Å wide at $T=0$ K are shown. The Al concentrations are $x=0.30$ ($x=0.57$) in the left(right) panel.

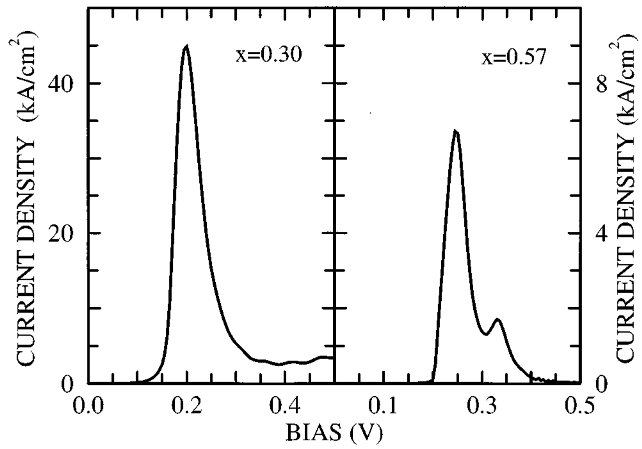

FIG. 3. Current density–voltage characteristics for the double barrier structure of Fig. 2(a).

A dramatic change in the J–V curve line shape with barrier height occurs. Referring to Fig. 2(a), the onset of the peak in Fig. 3 (left-hand side), coincides with the anticrossing of the quasibound state in the well with the Fermi energy. No structure in the J–V characteristics is present due to the anticrossing of the well and accumulation quasibound states. The drop of the current–density peak occurs when the level in the well goes below the potential bump in the spacer layer (see Fig. 1). The situation leading to this line shape is rather involved. Due to charge accumulation, the position of the accumulation layer level is nearly pinned. The collector barrier drops faster with bias than the emitter barrier, resulting in a strong asymmetry between T_e and T_c with a consequent suppression in the transmission probability peak[11] related to the coupling between the levels in the accumulation layer and double barrier. This picture can be changed by increasing the barrier heights, as shown in Fig. 3 (right-hand side). Now, higher barriers reduce the first current–density peak and a more opaque collector barrier enhances the transmission probability due to the coupling of the quasi-2D levels in the triangular and double-barrier quantum wells.

In Fig. 4 J–V characteristics for $L_s=600$ Å at $T=0$ K are shown. The other parameters are the same as in Fig. 3.

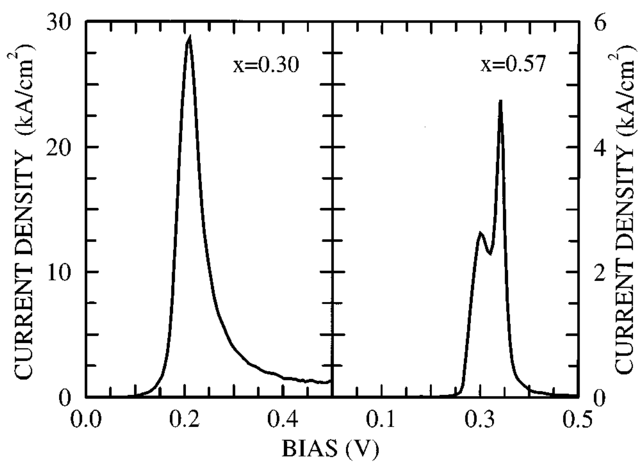

FIG. 4. Current density–voltage characteristics for the double barrier structure of Fig. 2(b).

Increasing the thickness of the spacer layer leads to a successive isolation of the accumulation layer. In other words, we observe that the top of the potential bump formed in the spacer layer region under applied bias approaches the Fermi energy. This results in a sharpening of the energy window for the 3D electrons (in the remote far-left emitter) to tunnel directly through the level in the double-barrier well. On the other hand, as can be seen from the energy position of the peak in Fig. 4 (left-hand side), low collector barriers still make the tunneling of 3D electrons the dominant tunneling path. Nevertheless, increasing barrier heights now makes the second peak (due to the coupling between the states) completely dominant in the *J–V* characteristics.

The main conclusion is that one has two limits for the line shape of the current density–voltage characteristics. The first one corresponds to a single highly asymmetric peak, abrupt at the lower bias side, due to tunneling of 3D electrons over the potential bump in the spacer layer. The second limit shows a doubly peaked structure, where the second peak is due to the coupling of the quasibound states in the accumulation layer and double-barrier quantum well. The difference between these two limits is a compromise of various effects, namely the effective transparency of the collector barrier, pinning of the accumulation layer level, and the width of the energy window between the Fermi energy and the top of the potential bump in the emitter region. Making the collector barrier less transparent, there is an enhancement of the tunneling probability when the quasibound states in the accumulation layer and double-barrier structure are coupled. At the same time, increasing the spacer layer thickness leads to a domination of this tunneling path on the tunneling of 3D electrons from the far-left emitter directly through the double-barrier level. We limit our analysis to structure with thin barriers due to numerical reasons. It should also be stressed that scattering effects[5] would tend to smear out the predicted features. For structures with thicker symmetric barriers, one should observe only the doubly peaked *J–V* characteristics. This lineshape change could be observed on a single sample with asymmetric barriers. Biasing this sample to have a thin collector barrier, one should observe a single peaked asymmetric *J–V* characteristics like in Fig. 3 (left-hand side). Biasing in the opposite direction, the *J–V* curve should show a double peak structure, as in Figs. 3 (right-hand side) or 4 (right-hand side). Evidence of these line shape changes can be seen in works concerned with bistability effects[12] and single electron tunneling.[13]

The authors would like to acknowledge Y. G. Gobato and J. A. Brum for critical reading of the manuscript. The financial support of CNPq, Conselho Nacional de Desenvolvimento Científico e Tecnológico, is also acknowledged.

[1] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).
[2] C. I. Huang, M. J. Paulus, C. A. Bozada, S. C. Dudley, K. R. Evans, C. E Stutz, R. L. Jones, and M. E. Cheney, Appl. Phys. Lett. **51**, 121 (1987); H. Riechert, D. Bernklau, J.-P. Reithmaier, and R. D. Schnell, Electron. Lett. **26**, 340 (1990); H. M. Yoo, S. M. Goodnick, and J. R. Arthur, Appl. Phys. Lett. **56**, 84 (1990).
[3] H. Onishi, T. Inata, S. Muto, N. Yokoyama, and A. Shibatomi, Appl. Phys. Lett. **49**, 1248 (1986); M. Cahay, M. McLennan, S. Datta, and M. S. Lundstrom, Appl. Phys. Lett. **50**, 612 (1987); W. Pötz, J. Appl. Phys. **66**, 2458 (1989).
[4] W. R. Frensley, Rev. Mod. Phys. **62**, 745 (1990).
[5] E. T. Koenig, C. I. Huang, and B. Jogai, J. Appl. Phys. **68**, 5905 (1990); Y. Galvão Gobato, F. Chevoir, J. M. Berroir, P. Bois, Y. Guldner, J. Nagle, J. P. Vieren, and B. Vinter, Phys. Rev. B **43**, 4843 (1991).
[6] T. Fiig and A. P. Jauho, Appl. Phys. Lett. **59**, 2245 (1991).
[7] B. F. Zhu and K. Huang, Phys. Rev. B **48**, 4575 (1993).
[8] F. W. Sheard and G. A. Toombs, Appl. Phys. Lett. **52**, 1228 (1988).
[9] M. Rossmanith, K. Syassen, E. Böckenhoff, K. Ploog, and K. von Klitzing, Phys. Rev. B **44**, 3168 (1991).
[10] R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[11] P. J. Price, Superlattices Microstruct. **2**, 213 (1986).
[12] A. Zaslavsky, V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Appl. Phys. Lett. **53**, 1408 (1988).
[13] M. Tewordt, L. Martín Moreno, J. T. Nicholls, M. Pepper, M. J. Kelly, V. J. Law, D. A. Ritchie, J. E. F. Frost, and G. A. C. Jones, Phys. Rev. B **45**, 14407 (1992).