Intrinsic bistability and hole-charge buildup in asymmetric *p*-type resonant-tunneling structures

R. K. Hayden,* L. Eaves, and M. Henini
Department of Physics, University of Nottingham, Nottingham NG7 2RD, United Kingdom

D. K. Maude and J. C. Portal
Service National des Champs Intenses, Centre National de la Recherche Scientifique, F38042 Grenoble, France and Laboratoire de Physique des Solides, Institut National des Sciences Appliquées, F31077 Toulouse, France

(Received 25 August 1993; revised manuscript received 20 December 1993)

A *p*-doped resonant-tunneling device with tunnel barriers having different transmission coefficients is investigated. The magneto-oscillations observed in the tunnel current when a quantizing magnetic field is applied along the direction of current flow are used to measure the resonant space-charge buildup in the quantum well. For one bias direction, intrinsic bistability is observed on one of the resonant peaks in the current-voltage characteristics.

It is now well established that under certain conditions, resonant tunneling[1] of electrons in double-barrier semiconductor heterostructures can give rise to a significant amount of negative space charge in the quantum well of the device.[2] This leads to the spreading of the resonant peak over a wide range of voltage, and in some cases can lead to an intrinsic bistability effect in the current-voltage characteristics, $I(V)$.[3–6] The bistability arises from an *electrostatic feedback effect*[3] in which an increase in bias voltage gives rise to charge buildup in the quantum well and leaves the resonant alignment of the emitter and quantum-well states unchanged. It can be enhanced in asymmetric devices in which electrons resonantly tunnel into the quantum well through an emitter barrier but have a much smaller transmission coefficient for tunneling out, due to the presence of a thicker[5] or higher[6] collector tunnel barrier. The resulting charge buildup in the quantum well has been determined directly by measuring the magneto-oscillations in the tunnel current when a magnetic field is applied parallel to the direction of current flow.[7] When the device is held at a constant bias, peaks in the tunnel current occur whenever a Landau level of the quantum-well subband passes through the quasi-Fermi energy of the electron gas in the quantum well.

Until recently, most work on resonant tunneling in double-barrier diodes has focused on *n*-type structures.[8] However, following the early experiments of Mendez *et al.*,[9] there has been renewed interest in the resonant tunneling of holes in *p*-type devices.[10–14] Despite the higher effective mass and increased scattering rate of holes, the magneto-oscillatory effect has recently been used to measure the hole space-charge density in the valence-band quantum well of a *p*-type resonant-tunneling device.[13] In this paper, we investigate an asymmetric *p*-type double-barrier resonant-tunneling device based on the GaAs/AlAs system in which the two AlAs barriers have different widths. Intrinsic bistability is observed in $I(V)$ on one of the hole tunneling resonances. The magneto-oscillatory effect in the tunnel current provides a measure of the hole space-charge buildup in the region of the bistability.

The device consists of a 4.2-nm GaAs quantum well formed between two AlAs tunnel barriers of thickness 4.5 and 5.7 nm. Undoped spacer layers of thickness 5.1 nm separate the two tunnel barriers from two Be-doped contact layers in which the doping is graded from 5×10^{17} cm^{-3} to 2×10^{18} cm^{-3} over a distance of 200 nm. A schematic diagram of the device is shown in Fig. 1 with the substrate biased positive. This bias configuration is defined as reverse bias and corresponds to holes tunneling into the quantum well through the thinner barrier and tunneling out through the thicker barrier. Under an applied voltage, a hole accumulation layer forms on the positively biased side of the device, adjacent to the emitter tunnel barrier. A depletion layer with negative space charge due to ionized acceptors forms on the negatively biased side, just beyond the

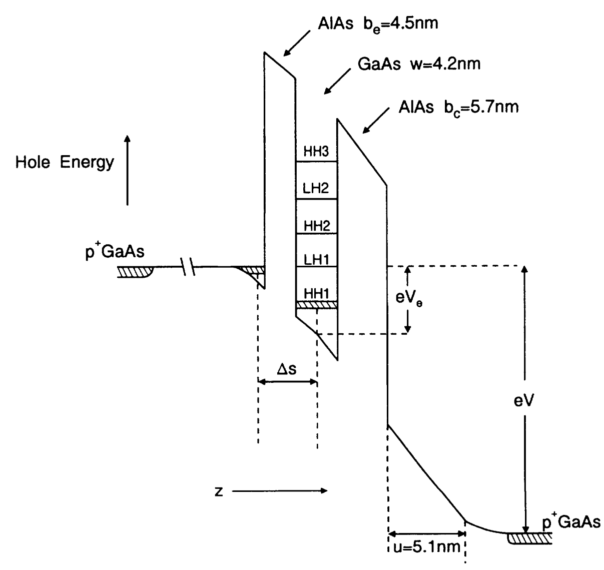

FIG. 1. Schematic energy-band diagram of the device in reverse bias.

spacer adjacent to the collector barrier. As the bias is increased, the energy of the quasi-two-dimensional hole subband in the accumulation layer aligns with the energies of the hole subbands in the valence-band quantum well, and resonant tunneling can occur. Figure 2 shows the $I(V)$ characteristics at a temperature of 4 K. In reverse bias, four peaks are observed in $I(V)$. By using resonant magnetotunneling spectroscopy with $\mathbf{B}\perp\mathbf{J}$,[11] we can positively identify the first three peaks as arising from resonant tunneling into the HH1, LH1, and HH2 subbands of the quantum well. Here, HHn and LHn refer to heavy and light hole, respectively; n is the quantum number of the respective envelope functions. The LH1 resonance shows a region of intrinsic bistability due to space-charge buildup in the quantum well. In forward bias, five resonant peaks are observed in $I(V)$. The first four correspond to resonant tunneling into the LH1, HH2, LH2, and HH3 subbands of the quantum well. The fifth peak at around 2 V is probably associated with the split-off valence band. A peak corresponding to tunneling into the HH1 subband is not observed in this bias direction. The forward-bias resonances occur at much lower voltages than the corresponding resonances in reverse bias, e.g., the peaks of the LH1 and HH2 resonances occur at 230 and 550 mV in forward bias and at 790 and 1300 mV in reverse bias. This difference is due to the additional potential drop in the depletion layer associated with the enhanced space-charge buildup in the quantum well in reverse bias.

In order to obtain quantitative information about the space charge in the quantum well, we have investigated the magneto-oscillations which are observed in the tunnel current at low temperatures (4 K) when a quantizing magnetic field is applied perpendicular to the plane of the quantum well, i.e., parallel to the direction of the current flow, $\mathbf{B}\|\mathbf{J}$. This technique has previously been employed to measure the sheet density of electrons in the accumulation layer and quantum well of n-type resonant-tunneling devices as a function of bias. The magnetic field quantizes the energy levels of the quasi-two-dimensional subbands in the accumulation layer and quantum well into Landau levels. In resonant-tunneling devices with n-type contacts and spacers layers, it is possible to identify magneto-oscillations due to thermalized electrons in both the emitter accumulation layer and the quantum well.[7] The oscillations occur only at low temperatures and arise from a modulation of the tunneling transmission coefficient due to the depopulation of Landau levels as they pass through the respective quasi-Fermi levels with increasing B. These measurements give the electron sheet densities n_a (a is the accumulation layer) and n_w (w is the quantum well) according to the relation

$$n_{a(w)}=2eB_{fa(w)}/h \ . \quad (1)$$

Here the factor 2 arises from spin degeneracy and B_f is the characteristic magnetic field of the magneto-oscillations and is given by $1/B_f=\Delta(1/B)$. Similar magneto-oscillations have been observed recently from the quantum well of p-type resonant-tunneling devices,[13] even though the Landau-level structure in the valence band is more complicated due to the admixing of the light- and heavy-hole states. In particular, the rate of sweeping of the quasi-Fermi level through the Landau levels is not necessarily periodic in $1/B$ for all values of B, due to the intersection of Landau levels.[15] However, the magneto-oscillations observed in these experiments arise from Landau levels with low index. In this case, the Landau levels, although not linear in B, do not intersect and Eq. (1) remains a good approximation. Mixing between light- and heavy-hole states only affects the Landau levels at higher hole energies significantly above the quasi-Fermi level in the quantum well. It is, therefore, possible to use Eq. (1) to determine the hole sheet density in the quantum well and the accumulation layer.

Figure 3 shows a series of low-temperature magneto-oscillations in the tunnel current for a range of forward- and reverse-bias voltages. In order to enhance the oscillations compared to the monotonically varying background current, we show second derivative plots of d^2I/dB^2. The magneto-oscillations have an amplitude at 8 T of typically 5% of the total tunnel current. For biases above ~ 0.5 V in reverse, they are surprisingly well defined, given that it is difficult to see the Shubnikov–de Haas effect from two-dimensional hole gases at temperatures above 2 K. In Fig. 4, we plot, for three values of bias, the inverse magnetic field values $1/B_n$, of maxima (integer n) and minima (half integer n) in d^2I/dB^2. It can be seen that the oscillations are quite accurately periodic in $1/B$, validating the use of Eq. (1).

The variation of the fundamental field B_f of the oscillations versus bias is shown by the series of data points (closed circles) in Fig. 2. The corresponding values of hole sheet density are given by Eq. (1). The errors in the values of B_f are estimated to vary from ± 0.2 T at -0.5 V to ± 2 T at -1.5 V. The most notable feature of this plot is the increase of B_f as the current increases to the peak of the LH1 resonance in reverse bias. Beyond this peak, in the region of the intrinsic bistability, the value of B_f drops abruptly. This variation of B_f with bias indicates that the magneto-oscillations are associated with a degenerate two-dimensional hole gas in the quantum well, since we expect the hole density to be a maximum on the peak of the resonance.[2,3,7,13] From Eq. (1), a value

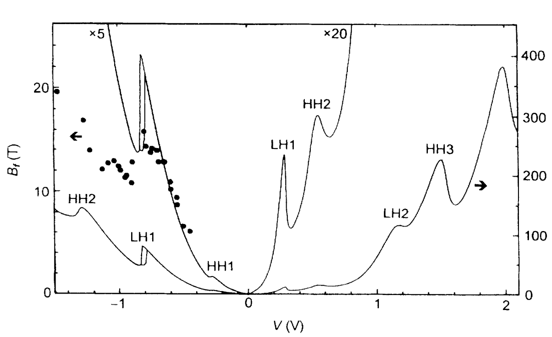

FIG. 2. The solid lines show the current-voltage characteristics $I(V)$ of the device at a temperature of 4 K. The closed circles show the variation of the fundamental field B_f of the magneto-oscillations in the tunnel current as a function of bias.

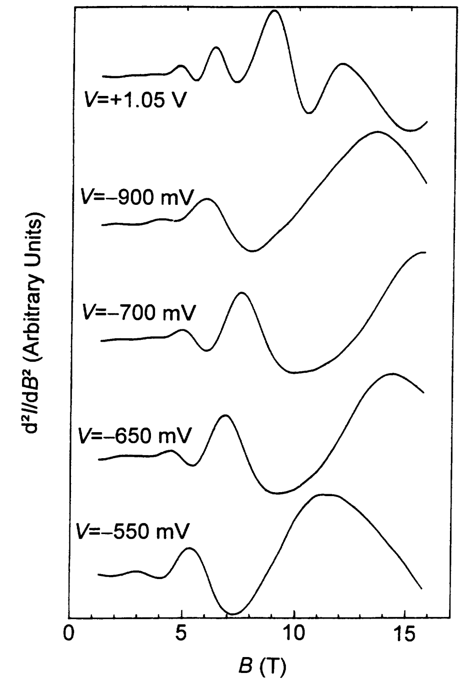

FIG. 3. The magneto-oscillations in the tunnel current (shown as second derivative plots d^2I/dB^2) at a series of different constant-bias voltages. The curves are obtained with magnetic field applied perpendicular to the plane of the quantum well, **B**||**J**, at a temperature of 4 K. Note that the top curve is in forward bias; the others are in reverse bias.

of $B_f = 15.8$ T close to the peak of the LH1 resonance in reverse bias gives $n_w = 7.6 \times 10^{11}$ cm^{-2}. At slightly higher reverse bias, at the minimum of $I(V)$, just beyond the bistable region, the value of n_w falls to 5.2×10^{11} cm^{-2}. Using an electrostatic model based on Poisson's equation to describe the space-charge distribution in the device,[13] we can estimate the width ΔV of the bistability due to this reduction of space charge as the device comes off the LH1 resonance. A value of $\Delta V = 100$ mV is deduced, compared with the measured value of 40 mV. This discrepancy may be due to the fact that we found it impossible to obtain a stable magneto-oscillation curve precisely at the peak of reverse-bias $I(V)$ curves; at bias voltages very close to the bistable region, we found that the current tended to switch to the low-current value as the field was swept.[16] The value of $n_w = 7.6 \times 10^{11}$ cm^{-2}, obtained at slightly lower reverse bias, may, therefore, underestimate the peak value of n_w.

The electrostatic model also allows us to estimate the difference in the peak positions of the LH1 resonances in forward and reverse bias. In forward bias the charge buildup in LH1 should be small since the current is ~6 times smaller than on the reverse-bias LH1 resonance and holes can readily tunnel out of the well through the thinner collector barrier. Assuming that $n_w = 7.6 \times 10^{11}$ cm^{-2} on the reverse-bias LH1 peak and is zero on the forward-bias peak, we estimate that the difference in voltage between the peaks of LH1 in forward and reverse bias is 0.31 V, compared to the measured value of 0.56 V. This discrepancy may also be due to the difficulty in measuring n_w at the peak of the reverse-bias bistable region. In addition, it is possible that the hole depletion beyond the collector barrier is incomplete so that the negative space-charge density is less than the density of acceptor dopants. Alternatively, the real acceptor doping density may be somewhat lower than the value (5×10^{17} cm^{-3}) specified in the expitaxial growth menu.

Finally, we note that in the forward-bias voltage range from ~0.8 to 2.0 V we observe clear magneto-oscillations with a B_f value that increases from 20 to 29 T, corresponding to a sheet density increasing from 9.7×10^{11} to 1.4×10^{12} cm^{-2}. A typical series of magneto-oscillations in forward bias is shown in the top curve of Fig. 3. These values of B_f are significantly higher than those observed over the same voltage range in reverse bias. As the amount of charge buildup in the quantum well should be smaller in forward bias, we attribute these magneto-oscillations to the Landau levels associated with the degenerate hole gas in the emitter accumulation layer. The corresponding values of hole sheet density in the emitter are consistent with our electrostatic model. Thus, the magneto-oscillations arise from the degenerate hole gas in the quantum well in reverse bias and from that in the emitter accumulation layer in forward bias.

In summary, we have observed intrinsic bistability in the $I(V)$ characteristics of an asymmetric p-doped resonant-tunneling device due to hole space-charge buildup in the quantum well. The magneto-oscillations observed in the tunnel current provide estimates of the sheet density of holes in the quantum well over a wide range of bias.

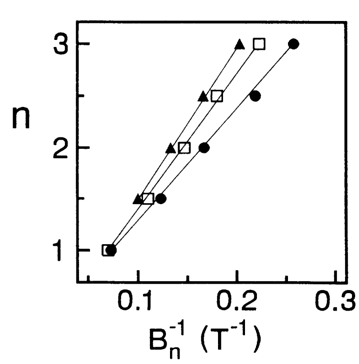

FIG. 4. Plots of the peak number n vs inverse magnetic field value B_n^{-1} for three reverse bias values: □: $V = -0.65$ V, ▲: $V = -0.7$ V, ●: $V = -0.9$ V. Maxima in d^2I/dV^2 correspond to integer n; minima to half integer n. The lines are intended as guides to the eye.

This work was supported by the Science and Engineering Research Council and by the ESPRIT Programme of the European Union. We are grateful to Dr. G. Hill of the University of Sheffield for processing the layers.

*Present address: Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 4DU, United Kingdom.

[1]L. L. Chang, L. Esaki, and R. L. Tsu, Appl. Phys. Lett. **24**, 593 (1974).

[2]B. Ricco and M. Ya Azbel, Phys. Rev. B **29**, 1970 (1984).

[3]V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. Lett. **58**, 1256 (1987); **59**, 1623 (1987); also, T. C. L. G. Sollner, *ibid.* **59**, 1622 (1987).

[4]T. J. Foster, M. L. Leadbeater, L. Eaves, M. Henini, O. H. Hughes, C. A. Payling, F. W. Sheard, P. E. Simmonds, G. A. Toombs, G. Hill, and M. A. Pate, Phys. Rev. B **39**, 6205 (1989).

[5]E. S. Alves, L. Eaves, M. Henini, O. H. Hughes, M. L. Leadbeater, F. W. Sheard, G. A. Toombs, G. Hill, and M. A. Pate, Electron. Lett. **24**, 1190 (1988).

[6]A. Zaslavsky, V. J. Goldman, and D. C. Tsui, Appl. Phys. Lett. **53**, 1408 (1989).

[7]M. L. Leadbeater, E. S. Alves, F. W. Sheard, L. Eaves, M. Henini, O. H. Hughes, and G. A. Toombs, J. Phys. Condens. Matter **1**, 10 605 (1989).

[8]*Resonant Tunneling in Semiconductors: Physics and Applications,* edited by L. L. Chang, E. E. Mendez, and C. Tejedor (Plenum, New York, 1991).

[9]E. E. Mendez, W. I. Wang, B. Ricco, and L. Esaki, Appl. Phys. Lett. **47**, 415 (1985).

[10]H. C. Liu, D. Landheer, M. Buchanan, and D. C. Houghton, Appl. Phys. Lett. **52**, 1809 (1988).

[11]R. K. Hayden, D. K. Maude, L. Eaves, E. C. Valadares, M Henini, F. W. Sheard, O. H. Hughes, J. C. Portal, and L. Cury, Phys. Rev. Lett. **66**, 1749 (1991).

[12]U. Gennser, V. P. Kesan, D. A. Syphers, T. P. Smith III, S. S. Iyer, and E. S. Yang, Phys. Rev. Lett. **67**, 3828 (1991).

[13]R. K. Hayden, L. Eaves, M. Henini, D. K. Maude, J. C. Portal, and G. Hill, Appl. Phys. Lett. **60**, 1474 (1992).

[14]R. K. Hayden, L. Eaves, M. Henini, T. Takamasu, N. Miura, and U. Ekenburg, Appl. Phys. Lett. **61**, 84 (1992).

[15]D. A. Broido and L. J. Sham, Phys. Rev. B **31**, 888 (1985).

[16]M. L. Leadbeater and L. Eaves, in *Proceedings of the Twentieth International Conference on the Physics of Semiconductors, Thessalonika, Greece,* 1990, edited by E. M. Anastassakis and J. D. Joannopoulos (World Scientific, Singapore, 1990), p. 1321.