

# Interference phenomena due to a double bend in a quantum wire

J. C. Wu and M. N. Wybourne  
Physics Department, University of Oregon, Eugene, Oregon 97403

W. Yindeepol, A. Weisshaar, and S. M. Goodnick  
Department of Electrical and Computer Engineering, Oregon State University, Corvallis, Oregon 97331

(Received 21 January 1991; accepted for publication 5 April 1991)

Narrow channel devices were fabricated using a split-gate high electron mobility transistor structure in which electrons are forced through a double-bend discontinuity. The low-temperature conductance shows a number of peaks in the lowest quantized conductance plateau which correspond qualitatively to resonance effects that are predicted for the geometrical discontinuities of the double bend.

Experimental studies of the conductance properties of split-gate field-effect transistors have evidenced quantum wave guide effects for electron propagation through such structures.<sup>1-3</sup> Since then, a number of studies in such structures have been reported which have shown effects associated with resonant tunneling through impurities,<sup>4</sup> superlattice effects due to a periodic grating,<sup>5</sup> and single electron charging phenomena<sup>6</sup> just to mention a few. Quantum interference phenomena are only apparent when the path length of electrons is below the inelastic mean free path. However, clear quantum waveguide effects due to artificial electron confinement may only be distinguished when the mean free path associated with elastic scattering (e.g., due to impurities and defects) is more than the dimensions of the waveguide itself. Thus, nanometer scale geometries and high mobility samples are necessary for the resolution of electron diffraction effects. In this letter, the low-temperature conductance properties of a narrow constriction in a high-mobility two-dimensional electron gas with a double-bend discontinuity are reported, and evidence for interference effects due to the bend are shown.

The theoretical effects of bend discontinuities on the transmission coefficient and current voltage characteristics of quantum wire structures have been reported by several groups.<sup>7-10</sup> The effect of a double-bend discontinuity has been discussed in detail using a mode-matching theory by Weisshaar *et al.*<sup>9,10</sup> There it was shown that strong resonance effects are present in the transmission coefficient versus energy due to the presence of a perpendicular single right angle bend. The effect of a double bend is to add further fine resonance features superimposed on the dominant resonance, with width and spacing in energy being dependent on the length of the bend.

To study the effect of bends on the conductance properties of quantum waveguide structures, the double-bend structure shown in Fig. 1 was fabricated. Here, a split-gate structure was utilized as shown in Fig. 1(a) in which the depletion region between the gate electrodes is used to constrict the electronic motion in the channel. The basic structure consists of a single  $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}/\text{GaAs}$  interface grown on undoped GaAs where the AlGaAs layer was doped  $1 \times 10^{18}/\text{cm}^3$  with a 150 Å spacer layer. The two-dimensional electron gas density in the unprocessed material was measured to be  $3.8 \times 10^{11}/\text{cm}^2$  with a mobility in excess of  $9 \times 10^5 \text{ cm}^2/\text{V s}$  at 1.7 K based on Hall and

Shubnikov-de Haas measurements. Depletion mode modulation-doped field-effect transistors (MODFETs) with and without split gates were fabricated via conventional optical lithography using Au/Ge ohmics to define the source and drain regions, and Ti/Au for the bonding pads. The transistors were mesa etched for isolation. After the ohmic contact deposition and anneal, electron beam lithography was used to define the double-bend split-gate structures used in this work.<sup>11</sup> Following thermal deposition of 5 nm titanium and 25 nm gold, the gate pattern was transferred to the heterostructure by a lift-off procedure. The final gates have an overall length of  $0.5 \mu\text{m}$  and a channel width of  $0.1 \mu\text{m}$ , as shown in Fig. 1(b).

Conductance measurements were made over the temperature range 0.07-5 K using a low-frequency (28.6 Hz) bridge arrangement in which the voltage across the sample

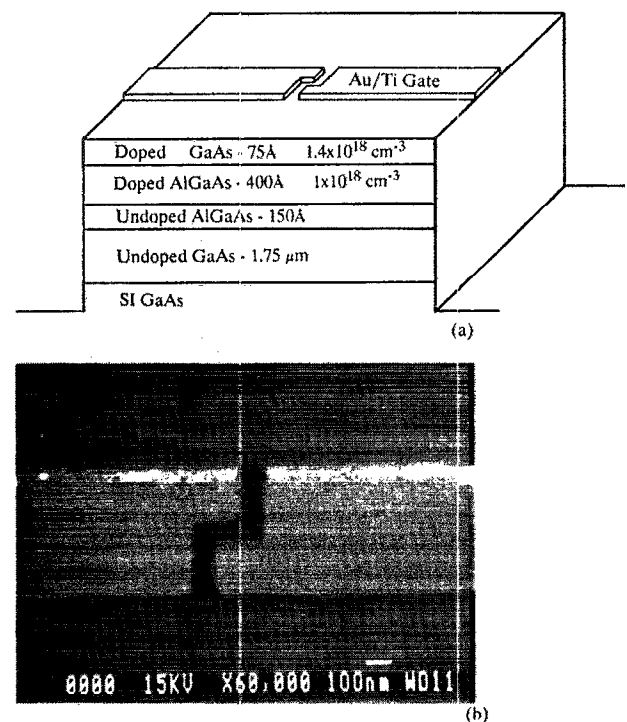


FIG. 1. (a) Schematic of the epitaxial layer structures and the split-gate structure used to realize a double-bend constriction. (b) Scanning electron micrograph of the split-gate structure.

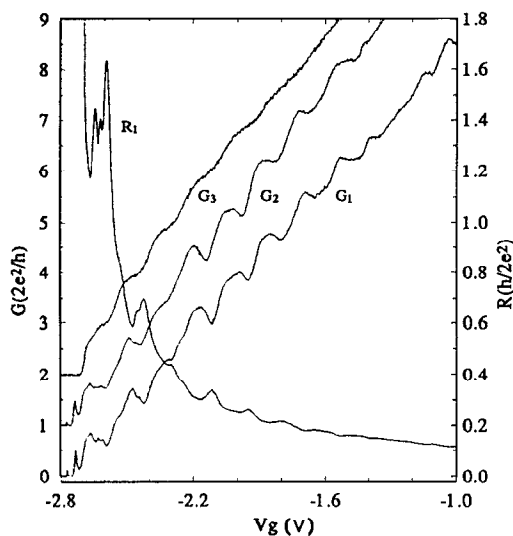


FIG. 2. Conductance as a function of gate voltage at three different temperatures, 100 mK ( $G_1$ ), 1 K ( $G_2$ ), and 4.2 K ( $G_3$ ).

was kept below the thermal voltage,  $kT/q$ , to avoid electron heating effects. In the absence of a gate voltage, the device resistance was typically 1 k $\Omega$  at 4.2 K. For negative gate voltages greater than 0.7 V, conduction was confined to the one-dimensional channel defined by the two halves of the gate. The measured conductance versus gate voltage for several temperatures is shown in Fig. 2. At 4.2 K (curve  $G_3$ ), quantized conductance plateaus in multiples of  $2e^2/h$  are observed as the channel width is reduced by the gate bias. Ten one-dimensional subbands are observed between the pinch-off of the two-dimensional electron gas (2DEG) and the pinch-off of the electrostatically defined channel. The plateau structure at 4.2 K is reproducible after repeated cycling between 4.2 and 300 K.

As the temperature is reduced from 4.2 K to 70 mK, the conductance plateaus are observed to resolve into a number of peaks, particularly the first plateau which is the most resolved. As may be seen in the comparison of the conductance for the three temperatures shown, the residual plateaus are no longer integer multiples of  $2e^2/h$ , but are reduced below these values. Figure 3 is an expanded plot of the first conductance plateau at a temperature of 250 mK. Little temperature dependence is observed as the temperature is lowered from 250 to 70 mK. The low-temperature curves themselves are reproducible after cycling between 4.2 K and low temperature. It is possible to identify six peaks in Fig. 3,  $a, a'$ , and the peaks labeled 1 through 4. The two sharp resonant peaks at low gate bias ( $a$  and  $a'$ ) have been reported by McEuen *et al.*<sup>4</sup> where they were argued to originate from resonant tunneling through impurity states in the constriction. Above peaks 1 through 4, there is a minimum followed by a rise to the second plateau which shows an inflection point. Higher plateaus show evidence of a similar set of peaks, although less resolved.

In Fig. 4, the calculated conductance versus channel width for a double-bend structure of the same nominal dimensions is shown using the mode-matching theory de-

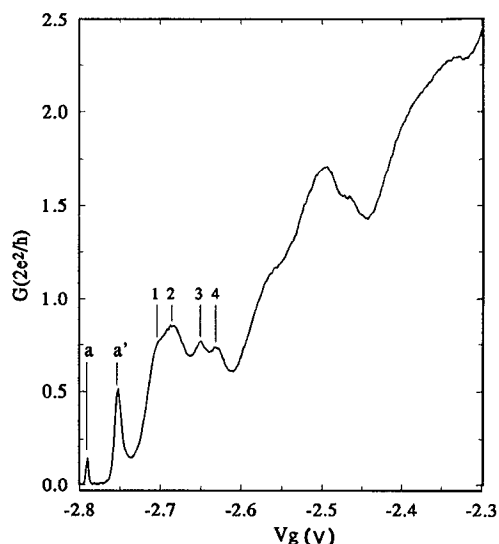


FIG. 3. Expanded plot of the conductance vs gate voltage at 250 mK for the lowest plateau.

scribed previously.<sup>9,10</sup> Here, only the bend itself is included in the calculation without considering the wider outside region. The calculated conductance using the temperature-dependent Landauer-Büttiker formula is shown at 0 and 4.2 K, and compared to the quantum steps calculated for a simple split-gate structure. The lowest plateau in the theoretical calculation is split apart into a series of resonant peaks, followed by a conductance minimum. The theoretical number of peaks in the first plateau increases with increasing length of the horizontal section of the double bend shown in Fig. 1(b). Similar structure is found in the higher plateaus, although not as well defined due to mode mixing in the higher subbands. At 4.2 K (the dotted curve), all of the fine resonant structure due to the double bend is washed out, and only a series of deformed plateaus

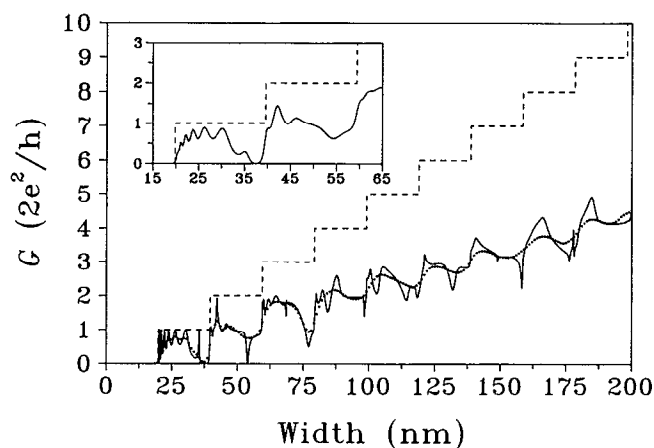


FIG. 4. Theoretical normalized conductance for a double-bend constriction of the same dimensions as the experimental sample as a function of the channel width for 0 K (solid curve) and for 4.2 K (dotted curve). The dashed curve is the normalized conductance without the bend discontinuity. The inset shows an expanded view of the calculated conductance at 2 K for the first two plateaus.

remain. The inset of Fig. 4 shows an expanded calculation of the lowest two plateaus at an intermediate temperature of 2 K, which resembles the experimental data in Fig. 3 in terms of the degree of broadening of the well defined peaks 3 and 4. The peaks *a* and *a'* do not appear in Fig. 4 because impurities have been neglected in the model. At the lowest temperature (70 mK), an inspection of the experimental conductance just before peak 1 shows two additional changes in slope which are suggestive of further peaks.

A one to one correspondence between the model used in Fig. 4 and experiment is not expected as the mode-matching theory assumes hard wall boundaries and uniform reduction in the channel width with gate voltage which is unrealistic for electrostatic confinement. This is evidenced by the fact that fewer plateaus are predicted in Fig. 4 below the nominal width of the constriction (100 nm) than are actually observed experimentally which implies the actual lateral confining potential is not as steep. In contrast to the theory, the experimental data show a temperature dependence in the overall approaching that of ideal quantum steps as the temperature is raised. The reason for this difference is not well understood at this time, although it is possible due to the temperature dependence of the phase coherence length.<sup>12</sup> However, recent experiments have shown the phase coherence length to be relatively temperature independent over the range of the present work.<sup>13</sup>

Although the peaks in Figs. 2 and 3 are suggestive of resonance phenomena associated with the double bend shown in Fig. 4, many of the global features have been observed by other groups in simple split-gate constrictions without intentional discontinuities. The deformation of the plateaus themselves have been observed by Brown *et al.*<sup>14</sup> and Timp *et al.*<sup>3</sup> at low temperature in straight constrictions, and found to be increasingly important as the length of the constriction increases. The total length of the structure shown in Fig. 1 is 0.5  $\mu\text{m}$ , which is on the same length scale as the structures in which length effects become important.<sup>3,14</sup> Brown *et al.* argued that the resonant structure observed in their work originated from longitudinal resonances due to the finite length of the constriction, a fact which is predicted by simple mode-matching theory.<sup>9,15</sup> More recently, Nixon *et al.*<sup>16</sup> have shown using a more sophisticated self-consistent numerical model including random impurity configurations, that the deformation of the plateaus may be explained by impurity-related scattering effects, and depend on the exact impurity distribution in the vicinity of the channel.

The present work is differentiated from these previous studies primarily by the resolution of several resonance peaks in the first plateau which qualitatively compare to

the predicted peaks in the first plateau expected from scattering due to the bend. No applied magnetic field was necessary to reduce weak localization effects in order to resolve the resonance structure shown in Figs. 2 and 3. The conductance plateaus persist well past 4.2 K as seen in Fig. 2, which argues that the one-dimensional subbands are well defined, with little collisional broadening due to background scattering. In addition, other structures with different geometrical discontinuities have been fabricated which show quite different resonant structure, which cannot be simply explained by a random impurity arrangement. These results will be discussed elsewhere.<sup>17</sup>

The authors would like to thank G. Pubanz for material growth and J. Lary for providing SdH measurements. The authors would also like to thank V. K. Tripathi for theoretical discussions related to this work. This work was partially supported by the National Science Foundation ECS-9015946 and the Office of Naval Research contract No. N00014-89-J-1894, as well as a grant from Tektronix, Inc.

- <sup>1</sup>D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, *J. Phys. C* **21**, L209 (1988).
- <sup>2</sup>B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, *Phys. Rev. Lett.* **60**, 848 (1988).
- <sup>3</sup>G. Timp, R. Behringer, S. Sampere, J. E. Cunningham, and R. E. Howard, in *Nanostructure Physics and Fabrication*, edited by M. A. Reed and W. P. Kirk (Academic, New York, 1989), p. 331.
- <sup>4</sup>P. L. McEuen, B. W. Alpheenaar, and R. G. Wheeler, *Surf. Sci.* **229**, 312 (1990).
- <sup>5</sup>L. P. Kouwenhoven, F. W. J. Hekking, B. J. van Wees, C. J. P. M. Harmans, C. E. Timmering, and C. T. Foxon, *Phys. Rev. Lett.* **65**, 361 (1990).
- <sup>6</sup>U. Meirav, M. A. Kastner, and S. J. Wind, *Phys. Rev. Lett.* **65**, 771 (1990).
- <sup>7</sup>H. U. Baranger, *Phys. Rev. B* **42**, 11479 (1990).
- <sup>8</sup>C. C. Lent and D. J. Kirkner, *J. Appl. Phys.* **67**, 6353 (1990).
- <sup>9</sup>A. Weisshaar, J. Lary, S. M. Goodnick, and V. K. Tripathi, *Appl. Phys. Lett.* **55**, 2114 (1989).
- <sup>10</sup>A. Weisshaar, J. Lary, S. M. Goodnick, and V. K. Tripathi, *SPIE Proc.* **1284**, 45 (1990).
- <sup>11</sup>J. C. Nability and M. N. Wybourne, *Rev. Sci. Instrum.* **60**, 27 (1989).
- <sup>12</sup>B. L. Altshuler, A. G. Aronov, and D. E. Khmel'nitsky, *J. Phys.* **15**, 7367 (1982).
- <sup>13</sup>T. Ikoma, in *Physics of Granular Nanoelectronics*, edited by D. K. Ferry, C. Jacoboni, and J. R. Barker (Plenum, New York, 1991), NATO ASI Series B, Vol. 210, pp. 255-276.
- <sup>14</sup>R. J. Brown, M. J. Kelly, R. Newbury, M. Pepper, B. Miller, H. Ahmed, D. G. Hasko, D. C. Peacock, D. A. Ritchie, J. E. F. Frost, and G. A. C. Jones, *Solid-State Electron.* **32**, 1179 (1989).
- <sup>15</sup>A. Szafer and A. D. Stone, *Phys. Rev. Lett.* **63**, 300 (1989).
- <sup>16</sup>J. A. Nixon, J. H. Davies, and H. U. Baranger, *Superlatt. Microstruct.* **9**, 187 (1991).
- <sup>17</sup>W. Yindepool, A. Chin, A. Weisshaar, S. M. Goodnick, J. C. Wu, and M. N. Wybourne, in *Proceedings of the International Symposium on Nanostructures and Mesoscopic Systems*, edited by M. A. Reed and W. P. Kirk (Academic, New York, to be published).