Negative differential conductance in quantum waveguides

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(Received 8 July 1994)

We discuss far-from-equilibrium electron transport in quantum waveguide structures at low temperatures. On slowly cooling the devices in the dark, the current-voltage characteristics are found to be similar to those of a quantum point contact. Exposure to light at low temperature alters the characteristics dramatically, with one or more regions of current-controlled negative differential conductance occurring. The characteristics can be returned to their prelight condition by annealing the samples above 120 K, which indicates that the effect is associated with the occupancy of *DX* centers in the $Al_xGa_{1-x}As$. We argue that the negative differential conductance arises from hot-electron bistabilities due to puddles of charge trapped in the waveguide by potential inhomogeneities associated with ionized *DX* centers.

Near equilibrium transport through quantum point contacts and quantum waveguides has received considerable attention over the past five years,[1] yet there have been few reports of nonlinear transport in these structures.[2,3] Near equilibrium transport occurs when the energy eV_{sd} associated with a bias V_{sd} applied across a quasi-one-dimensional channel or constriction is less than the subband separation, and is characterized by linear current-voltage (*I-V*) characteristics that have a slope $G = n2e^2/h$, where n is the number of occupied subbands. When eV_{sd} becomes comparable to the one-dimensional subband energy separation there is a difference in the number of subbands occupied for the forward and reverse currents which causes nonlinearities in the *I-V* characteristics. Furthermore, in the high source-drain bias regime it has been argued that the extra subbands made available by V_{sd} can act like current filaments and cause current controlled (*S*-type) negative differential conductance (SNDC) in the *I-V* characteristics.[4] Another mechanism that produces SNDC behavior has been identified in the far-from-equilibrium transport of pinched quantum-dot devices.[5] In these devices SNDC occurs when a critical thermionic current over the electrostatic potential defining the dot causes thermal runaway of the carriers in the dot which results in switching from a low to high impedance state.[6] In this paper we present measurements of the far-from-equilibrium *I-V* characteristics of single constriction quantum waveguides. A rich variety of instabilities are observed including single and multiple regions of SNDC, depending on the sample history in the cryostat. The SNDC occurs close to waveguide pinch-off and by analogy to similar behavior observed in quantum-dot devices we believe that the origin is related to heating of free carriers localized by inhomogeneities in the waveguide.

Overlapping split-gate quantum waveguides of length L and physical width 0.2 μm were fabricated on a molecular-beam epitaxy grown, uniform modulation-doped $GaAs/Al_{0.27}Ga_{0.73}As$ heterostructure, as shown schematically in the inset to Fig. 1. The silicon donor concentration was 1×10^{18} cm^{-3} in both the GaAs cap and the $Al_xGa_{1-x}As$ layer. The overlapping Schottky gate electrodes were defined by electron-beam lithography and comprised 25 nm of Au on top of 7.5 nm of Ti. The 4.2 K mobility and electron density of the ungated sample were 1×10^6 $cm^2/V\,s$ and 3×10^{11} cm^{-2}, respectively. With a sufficiently negative gate bias V_g applied to the gates, the two-dimensional electron gas (2DEG) beneath the electrodes is depleted forming a channel through which the electrons can propagate. Herein we report results for waveguides with $L = 0.1$, 0.2, and 0.5 μm, and a quantum point contact with $L = 0$ μm.

The samples were mounted in a pumped ^{4}He cryostat fitted with an infrared light emitting diode ($\lambda = 830$ nm) to enable *in situ* device illumination. Two measurement techniques were used to study the *I-V* characteristics of the devices as a function V_g. The equilibrium conductance was measured using a 70 μV amplitude, 23 Hz

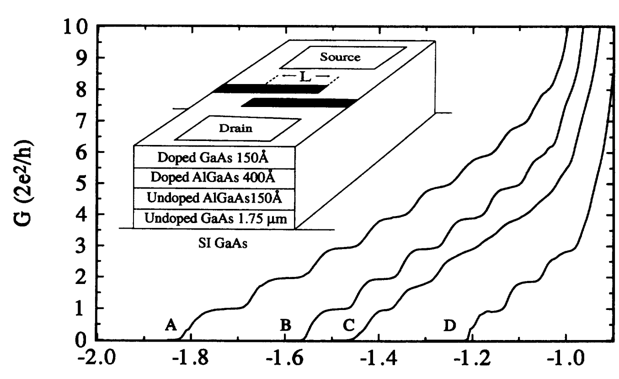

FIG. 1. The equilibrium conductance after light exposure of a zero overlap point contact (*A*) and the $L = 0.1$ (*B*) 0.2 (*C*) and 0.5 μm (*D*) waveguides. The inset is a schematic of the material and devices.

0163-1829/94/50(19)/14639(4)/$06.00

source-drain bias and a lock-in amplifier to detect current. Far-from-equilibrium experiments were performed with a four-terminal arrangement using a constant current dc source-drain bias and measuring $V_{\rm sd}$ across the device. The devices were cooled slowly in the dark to 1.2 K and the *I-V* characteristics were measured before and after sample illumination. The lattice temperature of the sample increased by less than 1 K during illumination and after returning to thermal equilibrium the sample conductance had increased by up to 5%, showing that silicon donor ionization had occurred.

Figure 1 shows the equilibrium conductance as a function of V_g for the waveguides and the point contact. As expected, the point contact has conductance plateaus at $n2e^2/h$. The $L = 0.1$ μm waveguide has five conductance plateaus close to $n2e^2/h$ indicating that the transverse orientation of the waveguides with respect to the source-drain axis does not significantly reduce the electron transmission coefficient from unity. Consistent with previous quantum waveguide studies,[7] longer devices always showed less ideal conductance quantization with structure in some of the plateaus probably caused by the random potential from ionized silicon donors.[8] The voltage at which the waveguides pinched off shifted by at most 0.5 V after light exposure, and the ideality of the equilibrium conductance depended on the illumination.

Figure 2 shows the source-drain characteristics as a function of V_g for the 0.5 μm waveguide before and after light exposure. For $V_{\rm sd}$ close to zero the slopes of both sets of characteristics show the conductance quantization. Before illumination the *I-V* characteristics (solid curves in Fig. 2) at higher values of $V_{\rm sd}$ are similar to those expected for an adiabatic point contact.[2] Assuming ballistic transport at finite $V_{\rm sd}$, we have modeled the *I-V* characteristics in this range using the finite temperature Landauer-Büttiker formalism,

$$I(V_{\rm sd}) = \frac{2e}{h}\int_0^\infty dE \sum_{n=1}^{\infty} T_n(E)[f^s(E,V_{\rm sd}) - f^d(E,V_{\rm sd})], \tag{1}$$

where $T_n(E)$ is the transmission coefficient, and $f^{s,d}(E, V_{\rm sd})$ are Fermi-Dirac distribution functions for the source and drain reservoirs. The energies $E_n = q\phi_0 - (qV_{\rm sd}/\alpha) + \epsilon_n$ where ϕ_0 is the potential in the constriction relative to the conduction-band edge of the 2DEG, ϵ_n are the subband energies and α is a parameter that describes the change in barrier height with potential across the waveguide.[6] We assume the transmission coefficient to be given by the local adiabatic model as,[9,10] $T_n(E) = (1+e^{-\beta_n(E-\epsilon_n)})^{-1}$, where β_n is a parameter describing the degree of coupling of the entrance and exit of the waveguide. Assuming simple hard wall confinement, this analysis provides good fits to the data prior to illumination as shown by the dotted curves in Fig. 2, using ϵ_n, β_n, and α as parameters for each gate bias. Additionally, a numerical mode matching analysis revealed no significant difference in the quantized conductance of the overlapping gate structures studied here compared to a straight constriction.[11]

Very different behavior is obtained in the same samples depending on the cooling rate and sample illumination, which is shown by the dashed curves in Fig. 2. At values of V_g and $V_{\rm sd}$ where prior to light exposure the conduction was close to zero, a rapid conductance rise was observed after illumination. The conductance rise moves to higher $V_{\rm sd}$ as V_g is made more negative. The *I-V* characteristics of the $L = 0.2$, 0.1, and 0 μm devices show a similar change after illumination. In some cases the rapid increase in conductance exhibited SNDC behavior. Figure 3 shows the *I-V* characteristics of the $L = 0.1$ μm device for forward and reverse $V_{\rm sd}$, which demonstrates the effect is asymmetric. The details at the onset of the conductance increase are changed, but the overall *I-V* characteristics are the same. In some devices two regions of SNDC occur, as shown in Fig. 4. The two SNDC regions have a different dependence on V_g, the first switching at $V_{\rm sd} \approx 6$ mV independent of V_g, the other switching at a value of $V_{\rm sd}$ that depends almost linearly on V_g.

Several transport mechanisms are possible sources of SNDC in these devices, including impact ionization,[12]

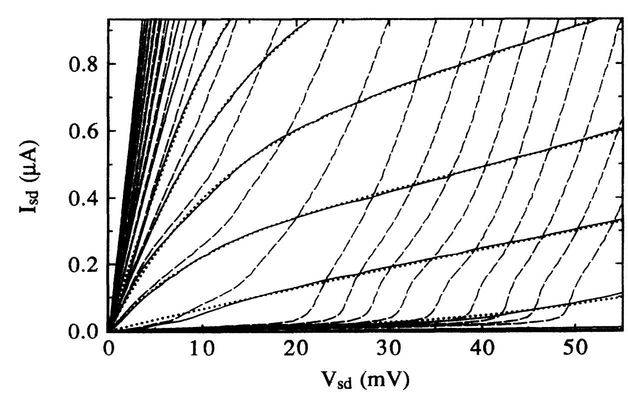

FIG. 2. The *I-V* characteristics of a $L = 0.5$ μm waveguide before (solid curves) and after (dashed curves) light exposure. The gate voltage is incremented in -20 mV steps from -0.7 V for the solid curves and -0.8 V for the dashed curves. The dotted curves are theoretical fits to the preexposed data.

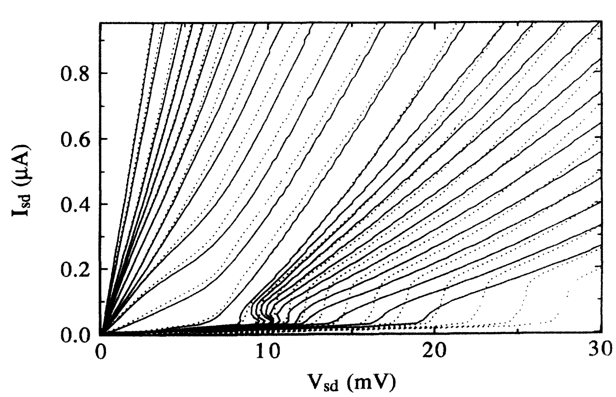

FIG. 3. The *I-V* characteristics of a $L = 0.1$ μm waveguide after light exposure. The solid and dashed lines show the effect of reversing the source drain bias. The gate voltage increment is -20 mV.

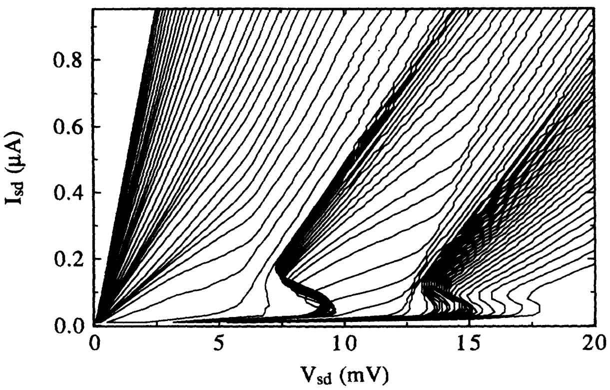

FIG. 4. The *I-V* characteristics of a $L = 0.1$ μm waveguide. The gate voltage increment is -20 mV.

Coulomb blockade,[13] and hot-electron runaway of confined carriers.[5,6] If impact ionization of donors was responsible for the SNDC, we would expect that further ionization of the donors by the light would decrease the effect. However, the opposite trend was observed in every sample studied. From the waveguide dimensions we estimate that SNDC due to the Coulomb blockade would have a low impedance state current at least three orders of magnitude below the measured value. The mechanism invoked to explain SNDC in quantum dots requires carrier confinement between two barriers.[10] Nixon *et al.*[8] have shown that in finite length quantum waveguides close to pinch-off, double barriers can be formed by the random potential from ionized impurities in the $Al_xGa_{1-x}As$. We believe that the formation of barriers in the electrostatic potential defining the waveguide, and puddles of charge trapped between the barriers, are responsible for the SNDC we observe.

In the $Al_{0.27}Ga_{0.73}As$ layers used in the present samples the lowest energy state of the silicon donors is a *DX* center.[14] *DX* centers have capture and emission barriers that govern the rate of electron exchange with the donor. At low temperatures these rates are exceedingly small. When the samples are first cooled slowly in the dark an equilibrium distribution of ionized donors is formed with only about 10% being ionized. The long range potential from this distribution introduces a random component to the electrostatic potential that defines the quantum waveguide.[8] In this equilibrium state we do not observe SNDC in any samples, which suggests that for the temperatures studied the potential barrier heights are insufficient to confine carriers. When the sample is illuminated at low temperature more donors are ionized. However, after the light has been switched off most of the ionized electrons remain in the conduction band of the $Al_xGa_{1-x}As$.[14] We have verified this conjecture through self-consistent calculations of the electronic states of the modulation-doped structure.[15] The degree of inhomogeneity in the potential forming the quantum waveguide will now be increased due to a larger concentration of ionized *DX* centers after illumination. This increases the likelihood that charge puddles exist in the waveguide, even after pinch-off. If the puddles behave as quantum dots, they may be excited by electrons injected from the contacts through the waveguide. Using the thermal runaway model reported earlier for quantum dots,[6] the first SNDC region shown in Fig. 4 is explained by effective barrier heights of about 10–20 meV with approximately 30–40 electrons trapped between them. Such SNDC behavior cannot be explained using the simple quasiadiabatic model [Eq. (1)].

Upon annealing the samples at about 120 K for 12 h, the *I-V* characteristics returned to their original, prelight exposed state. Mooney *et al.*[16] have shown that with an Al mole fraction of 0.27 and a silicon donor concentration of 1×10^{18} cm^{-3}, the time taken for one-half of the ionized *DX* centers to capture an electron is 10^4 s at 115 K, which is consistent with the times and temperatures necessary to anneal the present samples back to their pre-illuminated state. Furthermore, the shift in channel pinch-off voltage caused by the light is also consistent with *DX* center ionization.[16]

The model of hot-electron instabilities due to charge puddles in the waveguide qualitatively explains several other features of the data. For example, the differences when V_{sd} is reversed (Fig. 3) are predicted if the potential barriers are of different height. Barriers caused by the random potential may also explain the double SNDC behavior shown in Fig. 4. When more than two barriers influence the transport there is the possibility of two or more regions of trapped charge. In this case the thermal runaway model predicts multiple SNDC structure, the nature and scale of which depend on the position and size of the barriers, and whether the trapped regions can be considered to be in series or parallel.

In summary, we have shown that quantum waveguides at low temperatures can exhibit single or multiple regions of SNDC. These features may be explained by the formation of charge puddles in the waveguide due to potential inhomogeneities from *DX* centers. The puddles act like quantum dots which have been reported to have hot-electron instabilities in their *I-V* characteristics.

The authors would like to thank S. Subramanian for the self-consistent calculations we used here. This work was partially supported by the National Science Foundation ECS-9216768 and the Office of Naval Research N00014-93-1-0618.

[1] See references in *Solid State Physics*, edited by H. Ehrenreich and Turnbull (Academic Press, New York, 1991), Vol. 44.

[2] L. P. Kouwenhoven, B. J. van Wees, C. J. P. M. Harmans, J. G. Williamson, H. van Houten, C. W. J. Beenakker, C. T. Foxon, and J. J. Haris, Phys. Rev. B **39**, 8040 (1989).

[3] L. Martin-Moreno, J. T. Nicholls, N. K. Patel, and M. Pepper, J. Phys. Condens. Matter **4**, 1323 (1992).

[4] R. J. Brown, M. J. Kelly, M. Pepper, H. Ahmed, D. G. Hasko, D. C. Peacock, J. E. F. Frost, D. A. Ritchie, and G. A. C. Jones, J. Phys. Condens. Matter **1**, 6285 (1989).
[5] J. C. Wu, M. N. Wybourne, C. Berven, S. M. Goodnick, and D. D. Smith, Appl. Phys. Lett. **61**, 2425 (1992).
[6] S. M. Goodnick, J. C. Wu, M. N. Wybourne, and D. D. Smith, Phys. Rev. B **48**, 9150 (1993).
[7] 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 Press, Boston, 1989), p. 331.
[8] J. A. Nixon, J. H. Davies, and H. U. Baranger, Phys. Rev. B **43**, 12 638 (1991).
[9] H. A. Fertig and B. I. Halperin, Phys. Rev. B **36**, 7969 (1987).
[10] L. I. Glazman, G. B. Lesovik, D. E. Khmel'nitskii, and R. I. Shekhter, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 218 (1988) [JETP Lett. **48**, 238 (1988)].
[11] A. Weisshaar, J. Lary, S. M. Goodnick, and V. J. Tripathi, Appl. Phys. Lett. **55**, 2114 (1989).
[12] E. Schöll, J. Phys. (Paris) Colloq. **42**, C7-57 (1981).
[13] D. V. Averin and K. K. Likharev, in *Mesoscopic Phenomena in Solids*, edited by B. L. Altschuler, P.A. Lee, and R. A. Webb (Elsevier, Amsterdam, 1991), pp. 173.
[14] P. M. Mooney, J. Appl. Phys. **67**, R1 (1990).
[15] S. Subramanian (private communication).
[16] P. M. Mooney, N. S. Caswell, and S. L. Wright, J. Appl. Phys. **62**, 4786 (1987).