Observation of bistability in GaAs/AlAs superlattices

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We have experimentally observed a new kind of current bistability in the time-averaged current-voltage (I-V) characteristic of doped, weakly coupled GaAs/AlAs superlattices, in which the transport is dominated by sequential resonant tunneling between adjacent quantum wells. Time-resolved current measurements show that in some cases the bistability is correlated with a subcritical Hopf bifurcation, while in other cases a discontinuous change of the current oscillation frequency is observed in the bistable region. The origin of this new bistability is attributed to a change of the space charge layer in the superlattice involving charging and discharging effects, which creates a feedback to the external bias.
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Doped semiconductor superlattices (SLs) represent an ideal one-dimensional nonlinear dynamical system with a large number of degrees of freedom. The effective nonlinearity of the drift velocity originates from sequential resonant tunneling between adjacent quantum wells. Under external bias, doped superlattices are far from equilibrium exhibiting a large energy dissipation resulting in pattern-forming bifurcations. The formation of static electric-field domains has been reported by a number of researchers.[1–5] Under domain formation the applied electric field breaks up into distinct domains with well-defined field strengths separated by a space charge layer, the domain boundary. Since the location of the domain boundary is not uniquely determined for a given applied voltage, the current exhibits a bi-, tri- or even multistability under static domain formation.[6] If the carrier density is not sufficiently large, dynamic domains are produced by the spontaneous changes of the domain field strengths and/or the motion of the domain boundary, which can be observed as self-sustained current oscillations.[7–10] Periodic current oscillations have been observed between helium[7,8] and room temperature[9,10] with frequencies ranging from the kHz to GHz regime. Moreover, spontaneous chaotic current oscillations have also been found in this kind of a nonlinear dynamical system.[11,12] Complex bifurcation scenarios of self-oscillatory and stationary states including a bistability have been predicted previously for the parallel transport in modulation-doped heterostructures.[13]

In this letter, we have experimentally observed a new type of bistability in GaAs/AlAs superlattices by investigating the dependence of the self-sustained current oscillations on the applied voltage. Several bistable regions appear as a hysteresis of the time-averaged I-V characteristics. For some regions the bistability is correlated with production or quenching of self-sustained current oscillations. Another type of bistability is connected with a discontinuous change of the oscillation frequency. These bifurcations originate from the changes in the space charge distribution including local charging and discharging processes in the SL as the applied voltage changes. The charging or discharging effects produce a feedback to the applied voltage and result in a hysteresis and bistability.

The investigated sample consists of a 40-period, weakly coupled superlattice with 9.0 nm GaAs wells and 4.0 nm AlAs barriers grown on a (100) n^+-GaAs substrate by molecular beam epitaxy (MBE). The central 5 nm of each well are n-doped with Si at 3.0×10^{17} cm^{-3}. The SL is sandwiched between two highly Si-doped AlGaAs contact layers forming an n^+-n-n^+ diode. The sample is etched to yield mesas with a diameter of 120 μm. All experimental data have been recorded in a He-flow cryostat at 6 K using high-frequency coaxial cables with a bandwidth of 20 GHz. The time-averaged current-voltage characteristics are recorded with a Keithley SMU 236. The current oscillations are detected with a Tektronix CSA 803 sampling oscilloscope and an Advantest R3361 spectrum analyzer.

The top part of Fig. 1 shows the dc or time-averaged I-V characteristic at 6 K for two sweep directions. The I-V characteristic clearly exhibits three regions of bistability near 0.9 (A), 2.7 (B), and 3.4 V (C). The current plateau between 0.3 and 4.5 V originates from electric-field domain formation as described in Refs. 3 and 6. Since the plateau of the time-averaged I-V characteristic is rather structureless, the electric-field domains are not static. It has been shown that a traveling domain boundary results in periodic current oscillations.[7,8] The field strengths of the two domains are determined by resonant tunneling between adjacent wells involving the lowest electronic subband (C1→C1) for the low-field domain and the lowest and the second electronic subband (C1→C2) for the high-field domain.[8] In Fig. 2 the frequency spectra of the spontaneous current oscillations are shown as a function of the applied dc voltage between 0.9 and 3.4 V for sweeping the voltage from small to large values. The logarithm of the amplitude of the current oscilla-

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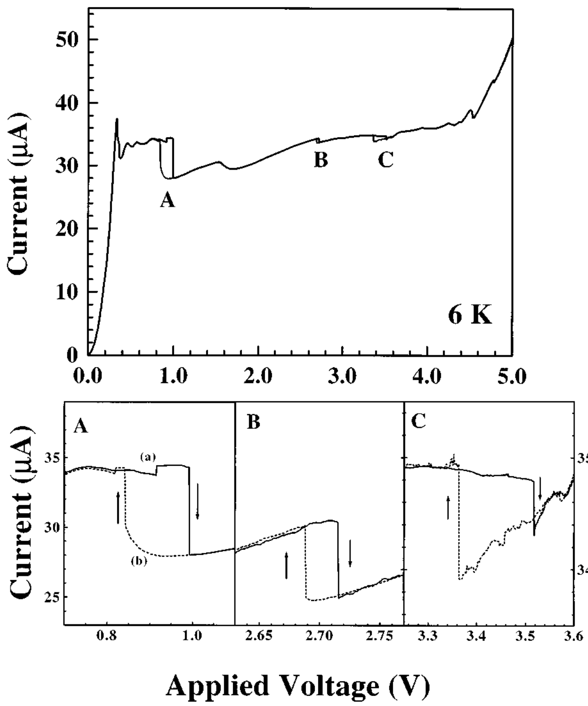

FIG. 1. Top: Time-averaged current vs applied voltage at 6 K. Bottom: enlarged sections of regions A, B, and C. The sweep directions are indicated. The labels (a) and (b) in the enlarged section of region A denote the voltages for the current oscillations in Fig. 3.

tions is indicated on a gray scale, where dark areas correspond to large amplitudes. The spectra contain a fundamental frequency of about 0.5 MHz and many higher harmonics of similar amplitude.[14] At the two voltages 0.9 (not shown) and 2.76 V the fundamental frequency and higher harmonics exhibit a sudden decrease and increase, respectively. For voltages larger than 3.4 V, the amplitude of the oscillations gradually decreases until it disappears at a voltage of 3.514 V.

The bottom part of Fig. 1 displays the enlarged sections of the bistable regions A, B, and C. In region C, the current exhibits a jump at 3.514 V, when the voltage is swept from low to high values. The jump occurs at a much smaller voltage of 3.36 V, when the sweep direction is reversed. The current oscillations disappear with increasing bias at 3.514 V, where the jump in the current occurs. When the applied bias is lowered from any value greater than 3.514 V, no self-sustained current oscillations appear, until at 3.356 V current oscillations appear. The observed oscillatory mode is the same for both sweep directions, but the oscillations disappear and appear at different voltages for the two sweep directions. The observation of this hysteresis in connection with the fact that the current oscillations disappear and reappear at a different voltage with a finite amplitude may indicate the existence of a subcritical Hopf bifurcation in region C. For a subcritical Hopf bifurcation, the bifurcation takes place from an unstable focus to an unstable limit cycle and a stable focus. Our interpretation is consistent with theoretical simulations which show that in this dynamical system a subcritical Hopf bifurcation with a small bistability occurs, when the oscillating mode is quenched at higher bias.[10,15]

The hysteresis in region B is correlated with a sudden change of the oscillating frequency. Although the frequency change is not very large, it is clearly visible in Fig. 2, in particular for the higher harmonics. The bistability in Fig. 1, however, is rather small. The sharp change of the oscillation frequency could originate from an abrupt redistribution of the space charge layer, which forms the domain boundary, involving a charging or discharging process. Since the density of the accumulated space charge is very large, the charging or discharging effect can produce a voltage feedback, which results in a sudden change of the oscillation frequency as well as a hysteresis in the time-averaged I-V characteristic. A stronger charging or discharging effect will lead to a larger change in the frequency, which in turn will produce a larger voltage feedback and hysteresis.

The hysteresis region A near 0.9 V, which is shown on an enlarged scale in the bottom of Fig. 1, has a more complicated structure. When the external dc voltage reaches 0.885 V, self-sustained current oscillations abruptly appear with a considerably larger frequency than for the other voltages of the plateau. In Fig. 3(a) the time-resolved current is shown for a voltage from this region [at 0.885 V labeled (a) in Fig. 1] with a fundamental frequency of 1.4 MHz. The time-averaged I-V characteristic exhibits a jump at about 0.9 V. As the voltage increases, the current oscillations change drastically with an abrupt decrease of the frequency. The corresponding trace is shown in Fig. 3(b), where the current is plotted at 0.867 V for a down sweep [labeled (b) in Fig. 1]. It is has the same frequency contents as for the up-sweep direction for voltages above 0.9 V (cf. Fig. 2). When the voltage is lowered from any value greater than 0.99 V, the frequency of the current oscillations remains low [such as in Fig. 3(b)] until a critical voltage of 0.84 V is reached, where the oscillation frequency jumps to a higher value again. At the same time the time-averaged current increases abruptly as shown in Fig. 1. When the voltage is decreased further to 0.82 V, the high-frequency current oscillations suddenly disappear. In this voltage regime there seems to be a more complex bifurcation scenario of the oscillations and the bistability. A subcritical Hopf bifurcation may play a role in addition to a jump in the current oscillation frequency.

Theoretical simulations have predicted three oscillatory

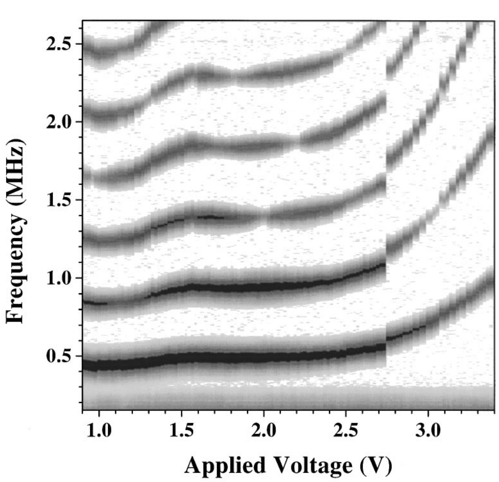

FIG. 2. Frequency spectra of the spontaneous current oscillations vs applied voltage at 6 K. The current power spectra are shown as a density plot on a logarithmic scale, where darker areas correspond to larger amplitudes.

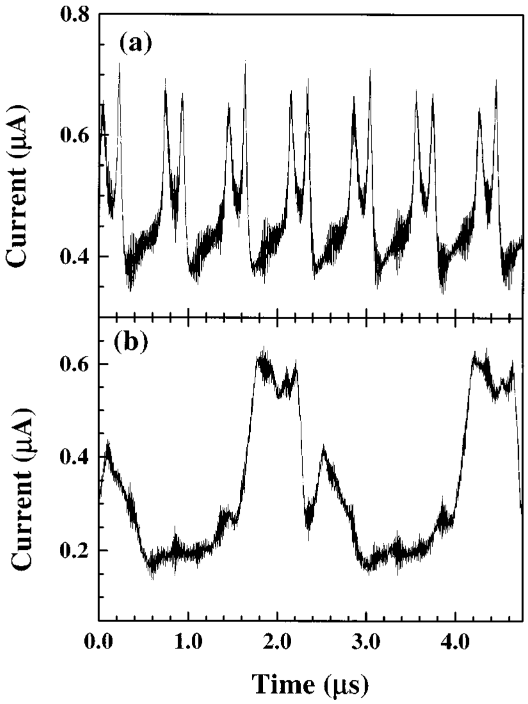

FIG. 3. Traces of the time-resolved current at 0.885 (a) and 0.867 V (b), which are typical for the up-sweep and down-sweep direction, respectively. The voltage positions are also shown in the enlarged section of region A in Fig. 1.

modes of the domains in this biased superlattice system.[10] When the bias is just above the onset of the instability, the current oscillations are induced by the oscillating electric field around an almost uniform stationary state. Therefore, no well-defined high-field domain develops, and the accumulated space charge density remains small. A second oscillatory mode appearing for intermediate biases is due to a recycling of the charged domain boundary, where the accumulated space charge density is now very large. The change of the oscillatory mode in region A is probably due to the formation of the high-field domain with the recycling mode, which is accompanied by the rapid buildup of the space charge region at the domain boundary. Thus, the increase of the space charge density can result in a strong feedback leading to a large bistability.

In conclusion, we have experimentally observed a new type of hysteresis due to a subcritical Hopf bifurcation and strong changes in the oscillatory modes of the domains. We would like to stress that, according to our experimental results, a subcritical Hopf bifurcation occurs at the onset of the instability at low bias instead of a supercritical Hopf bifurcation as predicted by theoretical simulations.

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