Quenching of the spontaneous current oscillations in GaAs/AlAs superlattices under domain formation

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(Received 10 May 1996; accepted for publication 5 June 1996)

Self-sustained current oscillations in a dc biased GaAs/AlAs superlattice exhibiting domain formation can be quenched by applying an external ac driving voltage with a large amplitude. The frequency of the driving voltage has to be much larger than the oscillation frequency and the well-to-well hopping frequency of the domain boundary. Under this condition, the oscillations of the domain boundary cannot follow anymore the ac driving signal. Consequently, for a fixed dc bias voltage the accumulated charge forming the domain boundary is confined within a single quantum well resulting in stationary domains.
[S0003-6951(96)01534-3]

Sequential resonant tunneling leads to an effective nonlinearity of the drift velocity in semiconductor superlattices (SLs). In a doped SL with an externally applied bias voltage, the effects of self-organization can result in the formation of electric-field domains. Under this condition, the applied electric field breaks up into two distinct domains separated by a space-charge layer, the domain boundary. As the applied voltage is increased, the well-to-well hopping of the domain boundary induces a series of regular discontinuities in the I–V characteristic. The number of jumps is correlated with the number of periods in the SL. Since their first observation in 1974,[1] stationary domains in SLs have been extensively investigated experimentally,[2–6] and theoretically.[7–9] However, very recently it was found that electric field domains in SLs can be unstable with an oscillating domain boundary, which moves over several periods.[10–13] The motion of the domain boundary results in spontaneous self-oscillations of the current with frequencies ranging from kHz to GHz. Therefore, semiconductor superlattices with an oscillating domain boundary may have important potential applications for microwave devices.

In this letter, we present the observation of the quenching of the current self-oscillations in GaAs/AlAs SLs by an external ac driving voltage with a large amplitude and high frequency. In addition to the fundamental oscillatory mode, a series of sharp current spikes are present occurring on a timescale much shorter than the fundamental oscillation. These spikes originate from the well-to-well hopping process of the accumulation layer forming the domain boundary. An ac driving voltage with a large amplitude can quench these oscillatory modes, if the period of the ac driving signal is considerably smaller than the well-to-well hopping time of the domain boundary. Under this condition, the time-averaged I–V characteristic exhibits the typical jumps of stationary electric-field domains.

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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 cryostate at 6 K using high-frequency coaxial cables with a bandwidth of 20 GHz. The time-average 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 ac driving voltage applied in addition to the dc bias voltage is provided by a Wavetek 81 function generator.

Figure 1 shows the time-resolved spontaneous current oscillations for an applied voltage of 2.77 V. The oscillations occur in the plateau of the time-average I–V characteristic as shown in the top part of Fig. 2. In this voltage range, the field

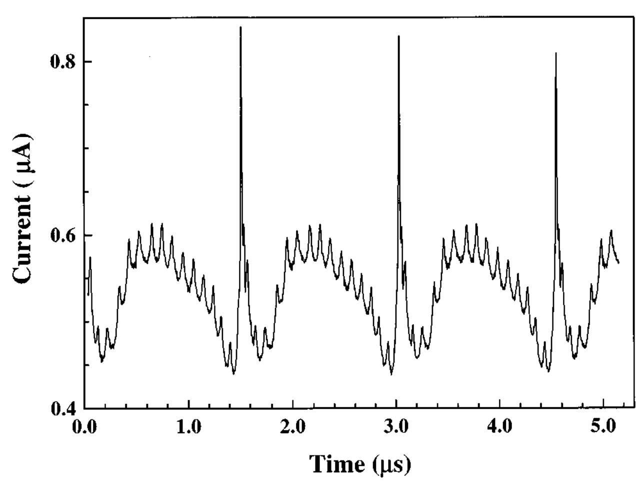

FIG. 1. Typical trace of the time-resolved current for a bias voltage of 2.77 V at 6 K without any external driving voltage.

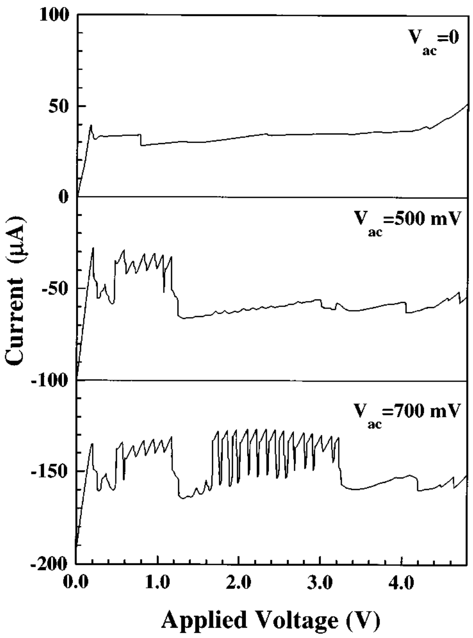

FIG. 2. Time-averaged current vs applied voltage for different amplitudes of the driving voltage with a frequency of 50 MHz at 6 K. The traces for $V_{ac} = 500$ and 700 mV have been shifted by -100 and -200 μA, respectively.

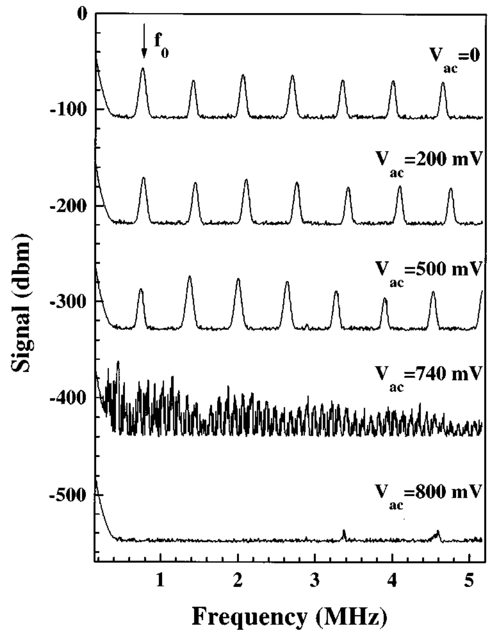

FIG. 3. Frequency spectra of the current oscillations for a fixed applied bias of 2.77 V using different amplitudes of the driving voltage with a frequency of 50 MHz at 6 K. The different spectra at $V_{ac} = 200$, 500, 740, and 800 mV have been shifted with respect to the data for no modulation amplitude by -110, -220, -330, and -440 dbm, respectively.

strengths of the two domains are determined by resonant tunneling between adjacent wells involving the lowest electronic sub-band ($C_1 \rightarrow C_1$) for the low-field domain and the lowest and the second electronic sub-band ($C_1 \rightarrow C_2$)for the high-field domain. Note that in addition to the fundamental oscillation with a period of 1.54 μs (650 kHz), fifteen very sharp spikes with a separation of about 100 ns are present within each longer-period oscillation. The observation of these spikes has already been reported in Ref. 14. The separation of these spikes is close to the well-to-well hopping time of the charge accumulating layer, which forms the boundary between stable domains.[6] Although the domain boundary can move spontaneously over several periods in this voltage range, the domain boundary only occupies a single period of the SL similar to the case of stationary domain formation implying that there is a well-defined domain boundary. However, due to the lack of translational symmetry in a weakly coupled SL along the SL direction, the motion of the boundary is not continuous.[6] This discontinuous motion of the domain boundary has already been observed in the time-average I–V characteristic for stationary domain formation.[3] The dwell time of the accumulating charge within a single quantum well is about ten times longer than the relocation time to the neighboring well.[6] The rapid relocation of the domain boundary is responsible for the enhancement of the current, i.e., the current spikes. The number of spikes indicates the number of periods involved in one complete oscillation.

Figure 2 shows the time-average current–voltage (I–V) characteristic for different driving voltage amplitudes using a frequency of 50 MHz. The period of the driving signal (20 ns) is much smaller than the dwell time of the accumulating electrons at the domain boundary, but close to the relocation time of the space-charge layer to the adjacent well. As the driving amplitude V_{ac} increases to 500 mV, regular features begin to appear in the time-averaged I–V characteristic. While these features are rather large for voltages below 1.2 V, they consist of only a small modulation of the average current for voltages above 1.2 V. However, at $V_{ac} = 700$ mV, the time-averaged I–V characteristics contains many more large current branches separated by jumps, which are similar to the I–V curve for stationary domain formation.[3] With increasing dc voltage, the domain boundary moves from well-to-well with an infinite dwell time resulting in the observed regular spikes. The average voltage spacing of 115 mV between two jumps is somewhat smaller than the energy difference of 135 meV between the first two electronic subbands ($E_{C2} - E_{C1}$). This observation is in agreement with previous photoluminescence measurements of the actual field strength of the high-field domain.[15] Furthermore, we also observed a bi- and tristability of the current for a fixed applied voltage similar to the case of stationary domains.[5] The appearance of the regular structures in and the multistability of the time-averaged I–V characteristics can be taken as a signature for the appearance of stationary domains, i.e., a quenching of the current self-oscillations. This interpretation is directly confirmed by looking at the frequency spectra for different driving amplitudes as shown in Fig. 3. The oscillatory modes in the low-frequency regime (about 1 MHz) have completely disappeared for $V_{ac} = 800$ mV.

The results shown in Fig. 3 have been obtained for a bias voltage of 2.77 V and a driving frequency of 50 MHz. Since the current oscillations of the domain boundary of 650 kHz in Fig. 1 consist of very sharp spikes, their Fourier transform contains many higher harmonics with rather equal amplitude. The frequency spacing between the peaks remains unchanged with increasing driving voltage amplitude up to $V_{ac} = 200$ mV. A frequency locking between the oscillatory mode of the domain boundary and the driving signal occurs up to driving voltage amplitudes of $V_{ac} = 600$ mV. Before the low-frequency oscillatory modes disappear ($V_{ac} > 600$ mV), a transition from frequency locking to chaos takes place through several bifurcations due to the competition between the oscillation of the domain boundary and the driving signal.[16] However, the discontinuities in the time-averaged I–V curve can already be observed for amplitudes of 500 mV, for which oscillations of the low-frequency mode are still clearly visible in Fig. 3. This observation demonstrates that the I–V characteristic can be divided in two parts, a stationary region with current jumps and an unstable region with low-frequency current oscillations. When the external ac field at the domain boundary exceeds the intrinsic ac field induced by the space charge layer, the space charge at the domain boundary will be completely confined within one well. Under this condition, the oscillations of the domain boundary will be completely quenched.

It should be noted that we cannot observe the regularly spaced discontinuities in the time-averaged I–V curve for large amplitudes of the driving signal, if the frequency of the driving signal is smaller than 10 MHz. In this case, the period of the driving signal is larger than the dwell time (~ 0.1 μs) of the domain boundary space-charge layer within a single quantum well. Therefore, the space-charge has sufficient time to move into the adjacent well within one period of the driving signal. Even for a large amplitude of the ac driving voltage, the space-charge layer cannot be confined within a single well and stationary domains will not form.

In conclusion, self-sustained current oscillations are quenched by an external ac driving voltage with a large amplitude, if the frequency of the driving signal is much larger than the well-to-well hopping frequency of the domain boundary. The time-averaged I–V characteristic shows the typical signature of stationary domain formation. An ac driving frequency smaller than the well-to-well hopping frequency cannot quench the oscillations.

The authors would like to thank J. Kastrup for experimental support and helpful discussions. This work was supported in part by the DFG within the framework of the Sfb 296.

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