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Relocation time of the domain boundary in weakly coupled GaAs/AlAs superlattices

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Static domain formation in doped semiconductor superlattices results in many branches in the current-voltage characteristic separated by a discontinuity in the current. The transition process from one branch to the next has been studied experimentally by adding an ac bias with different amplitudes to a dc bias close to a discontinuity and recording the time-resolved current. The relocation time of the domain boundary depends exponentially on the difference between the final static current and the maximum or minimum current value of the corresponding branch, which is reached before the relocation of the domain boundary takes place. A universal relationship between the relocation time and the current difference has been observed. [S0163-1829(98)50812-0]

The current-voltage (I-V) characteristic of doped, weakly coupled superlattices (SL's) exhibits—under formation of static electric-field domains—many sharp branches, which are separated by a discontinuity in the current. Under domain formation, the electric field in the SL's breaks up into two regions of constant field, which are separated by a domain boundary. The domain boundary is formed by a charge accumulation layer, which is confined to one or several SL periods, i.e., one or several quantum wells of the SL. When the applied bias voltage is swept from one current branch to the next across a discontinuity, the domain boundary moves exactly by one SL period.[1] Although there has been previously a large amount of investigations on static domain formation,[2–7] dynamical processes such as the domain formation time have only been studied recently.[8,9] However, the actual motion of the domain boundary, which occurs during a current jump from one branch to the next, remains unclear.

In this paper, we determine the relocation time of the domain boundary in a weakly coupled SL by fixing the dc bias (V_{dc}) near a discontinuity of the I-V characteristic and adding an ac square pulse voltage with different amplitudes (V_{ac}). The transient behavior of the current is measured as a function of V_{ac}. When the total applied bias sweeps across a current jump, e.g., from one branch to the next, the current response exhibits a delay, which becomes faster with increasing V_{ac}. The delay time depends exponentially on the difference between the final stabilized current and the maximum or minimum current of the initial current branch. A universal relationship between the decay time and the current difference has been observed for all cases.

The investigated sample consists of a 40-period, weakly coupled SL with 9.0 nm GaAs wells and 4.0 nm AlAs barriers grown by molecular beam epitaxy on a (100) n^+-GaAs substrate. 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 $Al_xGa_{1-x}As$ contact layers forming an n^+-n-n^+ diode. The sample is etched to yield mesas with a diameter of 120 μm. The experimental data are recorded in a He-flow cryostat at 5 K using high-frequency coaxial cables with a bandwidth of 20 GHz. The time-averaged current-voltage characteristics is recorded with a Keithley SMU 236. The current response to an ac voltage pulse is detected with a Tektronix CSA 803 sampling oscilloscope using the sampling head SD-32. The square wave voltage pulses are generated with a Wavetek 50 MHz pulse/function generator (model 81) with a width of 5 μs and a period of 10 μs. The pulse width and period have been chosen to be sufficiently long to allow the field distribution inside the SL to stabilize after the voltage is turned on or off in order to reset the field and charge distribution, before the next pulse arrives.

The time-averaged I-V characteristic at 5 K of the investigated sample is shown for the two sweep directions between 0 and -5.5 V in the inset of Fig. 1. The current plateau between -0.3 and -4.8 V originates from the electric-field domain formation as described in Refs. 4 and 7. An enlarged section of the I-V characteristic between -0.68 and -1.04 V is plotted in Fig. 1, which contains four branches and three discontinuities. The arrows indicate the sweep directions. Note that due to the multistability of the I-V characteristic,[7] the jump occurs at different voltages for different sweep directions.

In order to investigate the current response, we set the dc

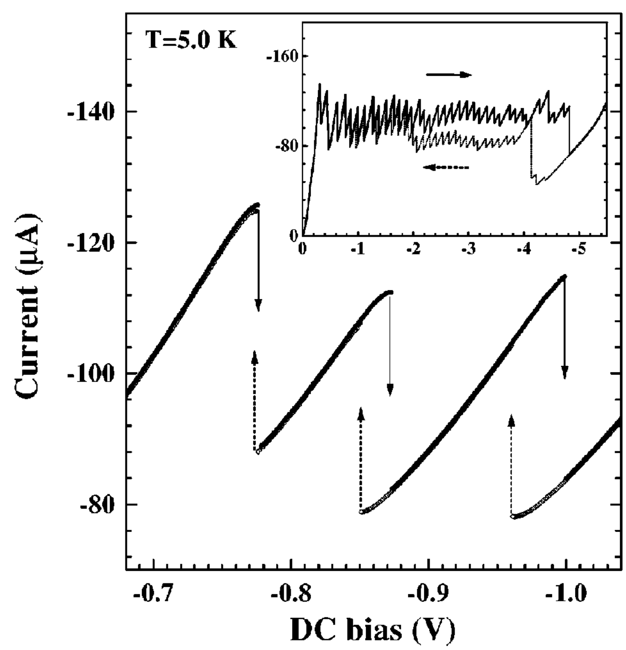

FIG. 1. Time-averaged I-V characteristics at 5 K for two sweep directions, from 0 to -5.5 V (●) and -5.5 to 0 V (◇). The complete sweep is shown for both directions in the inset.

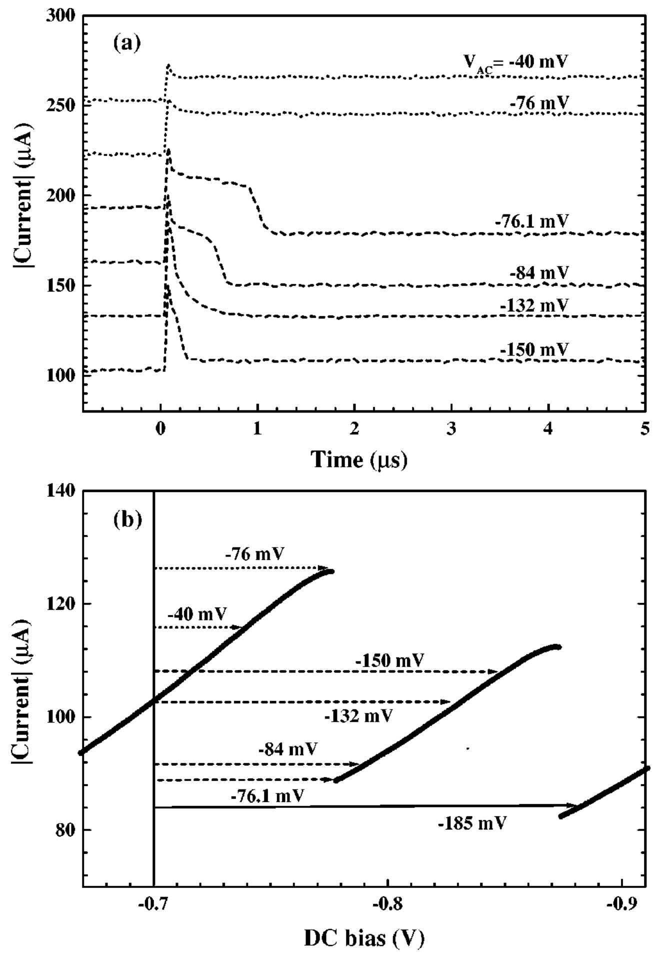

FIG. 2. (a) Current response vs time for different negative voltage pulse amplitudes at an applied dc voltage of -0.7 V and 5 K. The curves have been shifted vertically in units of 30 μA for clarity. (b) Section of the time-averaged I-V characteristic indicating the total voltage applied during a voltage pulse.

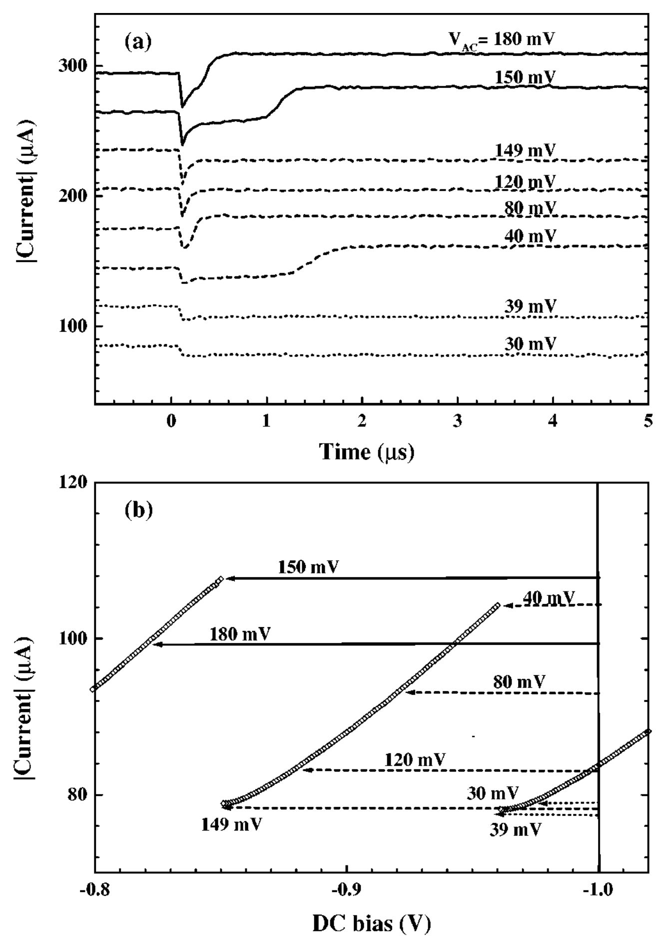

FIG. 3. (a) Current response vs time for different positive voltage pulse amplitudes at an applied dc voltage of -1.0 V and 5 K. The curves have been shifted vertically in units of 30 μA for clarity. (b) Section of the time-averaged I-V characteristic indicating the total voltage applied during a voltage pulse.

bias to -0.7 V near the first jump of the I-V characteristic in Fig. 1. By increasing the amplitude of the voltage pulse, the total voltage will eventually cross the first jump, and the current response should experience a strong change. Figure 2(a) displays a series of current responses versus time obtained for different amplitudes of the voltage pulse. All responses begin with a sharp spike, when the voltage pulse is turned on. These spikes are due to the displacement current of the sample, when a voltage step occurs, and mainly reflect the shape of the leading edge of the pulse.[9] We will focus on the current response within a single pulse width, i.e., the time range between 0 and 5 μs, where 0 μs is defined by the onset of the voltage step. For all responses, the current eventually reaches a stable value, which is equal to the dc current measured in the time-averaged I-V characteristic shown in Fig. 1. When $|V_{ac}|$ is less than 76 mV, the total bias results in a current value on the same branch as the dc bias. In this case, the current increases with increasing $|V_{ac}|$ and stabilizes instantaneously after the pulse is turned on. The situation for the total bias is shown by the arrows in Fig. 2(b), where an enlarged section of the time-averaged I-V characteristic of Fig. 1 for a sweep starting at 0 V is shown between -0.67 and -0.91 V. The dotted lines (arrows) in Fig. 2(a) [Fig. 2(b)] correspond to a total voltage on the initial branch and the dashed ones on the second branch. A strong change in the current response occurs, when $|V_{ac}|=76.1$ mV, indicating that the total voltage reaches the next branch. The current jump from the first to the second branch takes place within 0.1 mV. The decay of the current response is now prolonged. However, with increasing pulse amplitude, the decay is shortened. A similar behavior has also been observed, when the dc bias is fixed at other dc voltages within the plateau in the I-V curve shown in Fig. 1.

The same experiment has been performed by fixing the dc bias at -1.0 V and applying a positive ac voltage pulse. In this case, the magnitude of the total applied electric field is smaller than the initially applied one. The observed behavior is shown in Fig. 3(a). As long as the total bias is on the same branch as the dc bias, the current reaches the stable value within the step pulse resolution. However, at $V_{ac}=40$ mV, the current for the total and initial bias are on different branches [cf. Fig. 3(b)], and the current response is again delayed by about 1.5 μs. With increasing V_{ac}, the current response is shortened and reaches between 120 and 150 mV a time constant of the order of 100 ns. The second branch is reached at $V_{ac}=150$ mV, and the response is again delayed by about 1.1 μs.

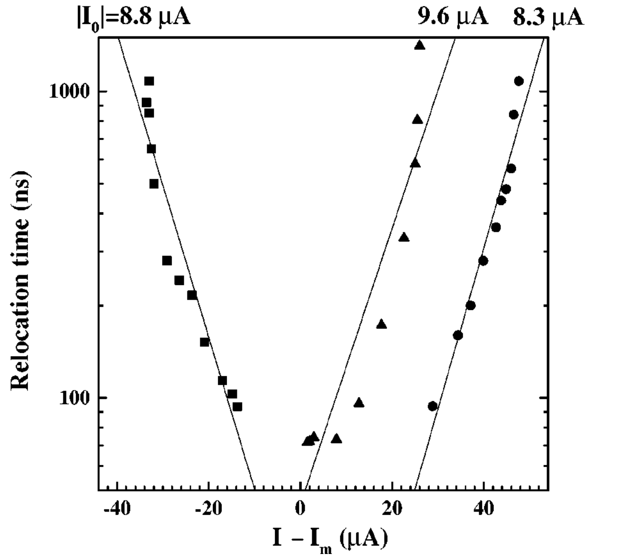

FIG. 4. Logarithm of the delay time vs current difference between final current value and the maximum or minimum current I_m of the initial branch. The squares correspond to the situation shown in Fig. 2(a), the triangles and circles to the situation in Fig. 3(a). The circles have been shifted horizontally by 20 μA. The solid lines are linear fits to the data points.

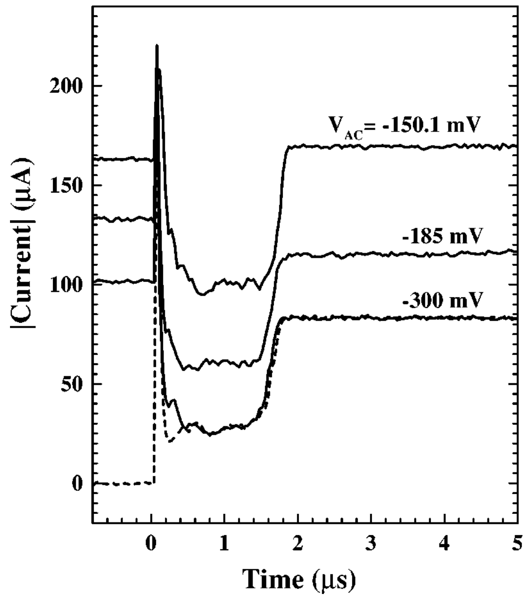

FIG. 5. Current response vs time for voltage pulse amplitudes of -150.1, -185, and -300 mV at an applied dc voltage of -0.7 V (solid lines) and for -1.0 V at an applied DC voltage of 0 V (dashed line) recorded at 5 K. The upper two solid lines have been shifted vertically in units of 30 μA for clarity.

The observed results can be interpreted in the following way. In contrast to previous experiments, where the bias was changed from 0 to its final value in order to study the formation of the boundary moving over many periods,[8,9] we clearly observe the relocation of the domain boundary over one or two periods. The domain boundary has already been formed before the ac bias is applied. Due to the large change in current, when V_{ac} is just sufficiently large to reach the next branch, the measured response is delayed. After the ac pulse has been turned on, the domain boundary first remains in the same well. The current value appears to be pinned at the maximum (minimum) value of the initial branch for the negative (positive) ac bias modulation in Fig. 2 (Fig. 3). After a certain time, the domain boundary relocates, and the current changes to its final stabilized value. The delay time is solely determined by the difference between the final stabilized current I and the maximum or minimum current I_m of the initial branch, which is reached before the current jump. A close examination shows that the relocation time τ_{rel} depends exponentially on this current difference $I-I_m$, i.e.,

$$\tau_{rel}=A\ \exp(|I-I_m|/I_0), \tag{1}$$

where A and I_0 denote constants. In Fig. 4, the relocation time τ_{rel} is plotted as a function of the current difference on a logarithmic scale for three different cases. The squares (triangles) correspond to the situation in Fig. 2(a) [Fig. 3(a)], where the initial and final voltages are located on adjacent current branches. The circles, which have been shifted horizontally by 20 μA in order to avoid an overlap with the triangles, correspond to data of Fig. 3(a), where the final voltage is on the third branch with respect to the initial voltage on the first branch. For all three data sets, the solid lines in Fig. 4, which denote linear fits to the data points, exhibit within experimental uncertainty the same slope. The resulting parameter $|I_0|$ is equal to 8.8, 9.6, and 8.3 μA for the squares, triangles, and circles in Fig. 4, respectively. Note that I_0 does not depend on the direction of the applied voltage pulse, nor on the number of branches between the initial and final voltage. This universal behavior indicates that local charging and discharging at the domain boundary plays a central role in the domain relocation process.

We now consider the current response at large negative pulse amplitudes, which have not been shown in Fig. 2. Figure 5 shows several current responses, when $|V_{ac}|$ is larger than 150 mV at $V_{dc}=-0.7$ V. In this case, the current initially decays to a lower level and then recovers to its stable value. Such a behavior does not change much, when $|V_{ac}|$ is increased further, as shown for $|V_{ac}|=185$ mV, where the total bias has reached the third branch [as indicated by the solid arrow in Fig. 2(b)]. From Figs. 5 and 2(a), it can be seen that at large pulse amplitudes, the current response exhibits a very different behavior, which indicates a domain formation mechanism different from that at smaller pulse amplitude. In Fig. 5, the bottom solid line shows the current response, when the bias is applied from -0.7 to -1.0 V. A very similar response is observed, when the dc bias is set to 0 V and an ac pulse of -1.0 V is applied, as shown by the dashed line in Fig. 5. The similarity between the two curves strongly suggests that they are due to the same domain formation mechanism, i.e., the monopole hopping mechanism over many periods, as reported in Refs. 8 and 9.

In conclusion, we have studied the dynamical process of domain relocation in a doped GaAs/AlAs superlattice by applying a dc bias near a current discontinuity and adding an ac bias with varying amplitude. For a final current value on the same current branch, the current response reaches its final value within the risetime of the voltage pulse. If the final current value is located on another branch, the time constant of the response depends exponentially on the difference between the final current and the maximum or minimum current values, which is reached before the relocation of the domain boundary takes place. The parameter for the exponential dependence is independent of the voltage pulse direction and number of branches involved in the relocation process.

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