Anomaly of the current self-oscillation frequency in the sequential tunneling of a doped GaAs/AlAs superlattice

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(Received 22 April 1999; revised manuscript received 24 November 1999)

An anomalous behavior of the current self-oscillation frequency is observed in the dynamic dc voltage bands, emerging from each sawtoothlike branch of the current-voltage characteristic of a doped GaAs/AlAs superlattice in the transition process from static to dynamic electric field domain formations. Varying the applied dc voltage at a fixed temperature, we find that the frequency increases while the averaged current decreases. Inside each voltage band, the frequency has a strong voltage dependence in the temperature range where the averaged current changes with the applied dc voltage. This dependence can be understood in terms of motion of the system along a limit cycle.

Following the original suggestion of Esaki and coworkers,[1,2] there has been a great deal of experimental[3] and theoretical[4] work on resonant tunneling in double barrier quantum well structures and superlattices. Under the right conditions, such structures have current-voltage characteristics with regions of negative differential resistance (NDR), leading to a range of important possible applications. Many interesting phenomena related to the NDR have been found in superlattices (SLs), ranging from a sawtoothlike branch of the current-voltage characteristic on the sequential resonance tunneling plateau,[5–10] current self-oscillations,[11–13] and chaos.[14] Self-oscillation has been observed in both doped and undoped SL systems.[10–12] The oscillation can be induced by continuous illumination of a laser light[13] or by a change of doping.[11] Recently, it has been shown that this self-oscillation can also be induced by applying an external magnetic field parallel to the SL layers or by varying temperature.[15,16]

Many theoretical approaches[17] have been used to understand the vertical transport properties of superlattices. It is known that the sawtoothlike branch of the current-voltage characteristic is related to the formation of stationary electric-field domains while the current self-oscillation is attributed to the motion of a domain boundary.[17] Very recently, a general analysis of the instabilities of the sequential tunneling current in superlattices has been carried out.[18] Based on the current-voltage characteristic of a single barrier, it shows that the presence of a NDR region can lead to the formation of both static and dynamic electric-field domains without assuming the origin of the NDR, whether it is due to any microscopic mechanism, such as off-resonance tunneling,[19] or the Gunn effect.[20] This theory predicts the existence of dynamic dc voltage bands emerging from each sawtoothlike branch of the current-voltage characteristic. The predictions were beautifully confirmed in a recent experiment.[21] According to the common wisdom, the frequency of the current self-oscillation under a dc voltage should have the same trend as the tunneling current. Namely, the frequency should be higher for a larger current. This is because of the general belief that the oscillation frequency is connected with the transit time frequency.[17] In this paper, however, we shall report an anomaly in the GaAs/AlAs superlattices. At a fixed temperature, the frequency increases with the applied voltage while the average current decreases in a dynamic dc voltage band. We show that this anomaly can be understood in terms of motion of the system along a limit cycle.

The doped GaAs/AlAs SL studied in this work was grown by molecular beam epitaxy. The SL consists of 40 periods of 14 nm GaAs well and 4 nm AlAs barrier. The SL is sandwiched between two n^+-GaAs layers. The central 10 nm of each GaAs well was doped with Si ($n=2\times10^{17}\,\mathrm{cm}^{-3}$). The sample was fabricated into $0.2\times0.2\,\mathrm{nm}^2$ mesas. The current-voltage, $I(U)$ characteristic of the sample was measured with a temperature range from 100 to 160 K by a HP4155A semiconductor parameter analyzer. In this study, we will focus on the second plateau corresponding to electron tunneling from the ground state in one well to the first excited state in the next in the low-field domain.[17] The inset of Fig. 1 is the sawtoothlike branch of the current-voltage characteristic for the whole second plateau at 140 K. The transition process from static to dynamic electric-field domain formations caused by increasing sample temperature is shown in Fig. 1 in the range of 2.68–2.94 V on the second plateau. Four sawtoothlike branches are observed. At $T=140\,\mathrm{K}$, all branches correspond to static electric-field domain formation. At $T=145\,\mathrm{K}$, a dynamic dc voltage band (indicated by open symbols in Fig. 1) appears in each of the sawtoothlike current branches. Within the dynamic dc voltage bands, the current experiences an oscillation in time, self-oscillation. In

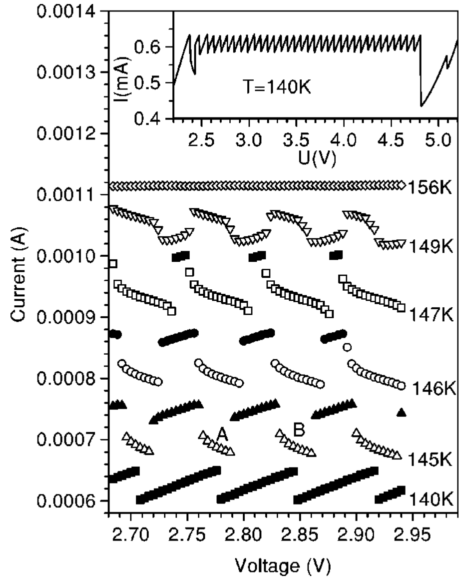

FIG. 1. $I(U)$ curves measured at 140, 145, 146, 147, 149, and 156 K showing the transition process from static to dynamic electric-filed domain formation on the second current plateau in the range of 2.7–2.94 V. Four sawtoothlike branches are observed. Open symbols indicate the dynamic region, current self-oscillation, while solid symbols indicate the static region. The inset is $I(U)$ for the whole second plateau at 140 K. $I(U)$ is the averaged current in the dynamic regions. Curves are offset for clarity. From bottom, $T=140$ K (square), $T=145$ K (up triangle), $T=146$ K (circle), $T=147$ K (square), $T=149$ K (down triangle), $T=156$ K (diamond).

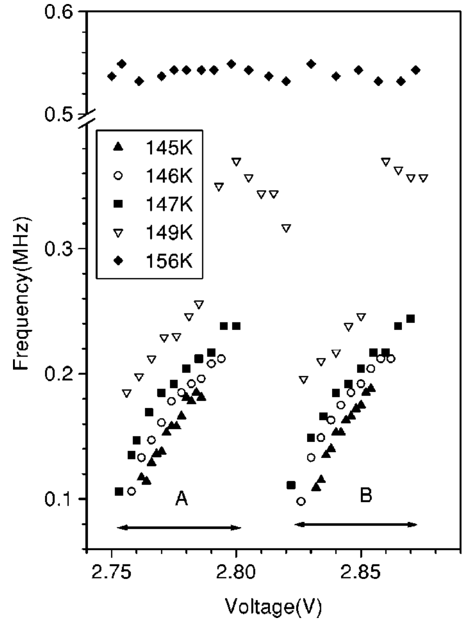

FIG. 2. Voltage dependence of the current self-oscillation frequency in the dynamic dc voltage bands of Fig. 1 in the range of 2.75–2.9 V. There are two bands, indicated by A and B, respectively, in this range when the temperature is higher than 140 K. Above 150 K, two bands join together, and the oscillation frequency is not very sensitive to the temperature in contrast to the case when the temperature is between 145 and 150 K. $T=145$ K (solid square), $T=146$ K (open circle), $T=147$ K (solid up triangle), $T=149$ K (open down triangle), and $T=156$ K (solid diamond).

other words, dynamic electric-field domain formation is observed. These dynamic dc voltage bands expand towards the higher-voltage side within each sawtoothlike current branch and squeeze out the static regions (indicated solid symbols in Fig. 1) in which static electric-field domains are formed. Above 149 K, all dynamic dc voltage bands join up together to turn the whole plateau into dynamic electric-field domain formation. The averaged current decreases with the dc bias in a given dynamic dc voltage band in the temperature range from 145 to 147 K. This indicates that the system is in the NDR region. At 149 K, each dynamic dc voltage band consists of two different parts within which the averaged current decreases with bias in one part while the current increases slightly with bias in the other. The current becomes more and more flat when the temperature increases further (as shown in Fig. 1 for 156 K).

Figure 2 is the voltage dependence of the current self-oscillation frequency for these dynamic dc voltage bands A and B as indicated in Fig. 1. It shows (1) the frequency increase with applied voltage before the dynamic dc voltage bands join up together (145, 146, 147 K) and (2) that the frequency does not have a voltage dependence at 156 K when the average current is insensitive to the applied voltage. It is peculiar to notice that the frequency increases with the dc bias although the averaged current decreases in the same bias region. A larger current means that the system is more capable of transferring charges. In turn, it should take less time for the system to move from one state into another. Therefore, the behavior in Fig. 2 is against the common wisdom that the frequency should be lower for a smaller tunneling current.[17]

In order to understand the surprising voltage dependence of the oscillation frequency in Fig. 2, we follow the theory of Ref. 18. We consider a SL system consisting of N quantum wells. An external bias U is applied between the two end wells. Current flows perpendicular to the SL layers. From the equations obtained from Ref. 18, equations for V_i's, bias on the ith barrier, are

$$\frac{1}{k}\dot{V}_{i-1}+I_{i-1}(V_{i-1})=\frac{1}{k}\dot{V}_i+I_i(V_i), \tag{1}$$

where $\dot{V}_i$ is the time derivative of V_i. $I_i(V_i)$ is the current through the ith barrier at bias V_i. k is a constant $4\pi l/(A\epsilon)$ where ϵ,A, and l are the permittivity, cross section, and periodicity of the SL, respectively.

In Ref. 18, we showed that temporal current self-oscillation is due to the generation of a limit cycle around an unstable steady-state solution (SSS) which is, in turn, caused by the NDR. The arguments for the limit cycle are as follows. Assume that the only SSS is an unstable fixed point of the system. A small deviation from this point will produce drastic consequences, the direction of all flow being outwards from this point. However, because the potential difference between two adjacent wells cannot exceed the applied bias, an unstable fixed point must be attractive in regions far away from the fixed point. Local repulsion and global attraction will force the system to travel along a closed curve, limit cycle, around the unstable fixed point. In this simple case, the system undergoes a periodic motion. The frequency of the periodic motion is the inverse of the time for the system to complete a cycle.

Equation (1) indicates

$$J=\frac{1}{k}\dot{V}_i+I_i(V_i), \tag{2}$$

which should be the same for all barriers. The physical meaning of J is the total current through the system with the first term to be the displacement current and the second term to be the current caused by the motion of charge carriers. Thus, the rate that V_i changes with time is

$$\dot{V}_i=k[J-I_i(V_i)]. \tag{3}$$

The total current remains a constant along a limit cycle around an unstable fixed point. If the diameter of the limit cycle around an unstable fixed point is D, then the frequency of the current of self-oscillation ω should be

$$\omega=k[J-I_i(V_i)]/D. \tag{4}$$

If I_i decreases with increase of the applied voltage, the oscillation frequency increases. Thus, this equation explains well the following experimental features. (1) The anomalous voltage dependence in Fig. 2 can now be understood as follows. At 145, 146, and 147 K an increase in the bias, I_i decreases because the system is in the NDR region as demonstrated in Fig. 1. Therefore, ω increases according to Eq. (4). At 149 K, $I(U)$ has very complicated behavior; the voltage dependence of the frequency is also complicated. (2) The averaged current curve becomes more and more flat as the temperature increases. Equation (4) says that the frequency should only weakly depend on the external bias in a dynamic dc voltage band. This is exactly what we observed in experiments at 156 K (Fig. 2).

From the limit cycle generation as the origin of the current self-oscillation, we show that the frequency is proportional to the displacement current rather than the total current as the common wisdom expects. The anomaly of the current self-oscillation frequency in the sequential tunneling of superlattices can be attributed to the NDR effects in the following way that the decrease of the charge carrier current leads to the increase of the displacement current which, in turn, leads to the increase of voltage charge rate. Before we end this paper, we would like to point out that, although we do not know how to compute the size of a limit cycle, a limit cycle is stable in the region of dynamic electric-field domain formation according to chaos theory.[22] Therefore, one expects that the diameter of a limit cycle, D, should weakly depend on the external bias. In summary, we observed that the current self-oscillation increases with the external bias inside a dynamic dc voltage band while the averaged current decreases with the external bias in the same region. This dependence is understood as the motion of the system along a limit cycle around an unstable fixed point in the NDR region.

We would like to thank Professor P. Sheng and Dr. Y. Q. Wang for many valuable comments and suggestions. One of us (X.R.W.) would like to acknowledge Professor Q. Niu, Professor B. L. Hao, and Professor C. S. Ting for stimulating discussions. He would also like to thank the hospitality of The Center for Theoretical Science, Taiwan. This work was supported by UGC, Hong Kong, through RGC and RGC/DAG grants.

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