Dynamic dc voltage band observed within each current branch in the transition from static to dynamic electric-field domain formation in a doped GaAs/AlAs superlattice

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A dynamic dc voltage band was found emerging from each sawtooth-like branch of the current–voltage characteristics of a doped GaAs/AlAs superlattice in the transition process from static to dynamic electric-field domain formation caused by increasing the sample temperature. As the temperature increases, these dynamic dc voltage bands expand within each sawtooth-like branch, squeeze out the static regions, and join up together to turn the whole plateau into dynamic electric-field domain formation. These results are well explained by a general analysis of stability of the sequential tunneling current in superlattices. © *1999 American Institute of Physics.* [S0003-6951(99)04443-5]

In the last few years, self-sustained temporal current oscillations, or so-called current self-oscillations, under a fixed dc bias corresponding to dynamic electric-field domain (EFD) formation[1] have been observed in weakly coupled semiconductor superlattices (SLs).[2–6] It has been shown that the current self-oscillation only occurs within a certain range of carrier concentration present in these SLs. However, above this carrier concentration range the current–voltage characteristics of these SLs exhibit discontinuities on the sequential resonance tunneling plateau and show a series of sawtooth-like current branches corresponding to static EFD formation.[7,8] Recently, it has been shown that by applying an external magnetic field parallel to the SL layers or increasing the SL sample temperature can also produce the transition between static and dynamic EFD formation.[9] These results are well explained by a general analysis of the stability of the sequential tunneling current in superlattices based solely on the magnitude of the negative differential resistance[10] (NDR) region in the tunneling characteristics of a single barrier.[11] The transition is a consequence of changing NDR caused by increasing magnetic field and temperature.

In this letter, the SL sample temperature (T) induced transition process between static and dynamic EFD formation was investigated in detail. A phenomenon was observed: During the transition process, the dynamic dc voltage band, within which temporal current self-oscillation was observed, was found emerging from each sawtooth-like branch in the transition process. These dynamic dc voltage bands expand within each sawtooth-like branch, squeeze out the static regions in which static EFDs are formed, and join up together to turn the whole plateau into dynamic EFD formation as the temperature increases. These results are well explained by a general analysis of the stability of the sequential tunneling current in superlattices.[10] Based on a simple model, we show that the current self-oscillations, i.e., dynamic EFD formation, occur initially within a certain dc voltage range, i.e., dynamic voltage band, on each sawtooth-like branch. The dynamic voltage bandwidth[12] is increased with increasing magnitude of NDR.

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 wells and 4 nm AlAs barriers. 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 $0.2\times0.2\,\mathrm{mm}^2$ mesas. The current–voltage $I(U)$ characteristics of the sample were measured with the temperature ranging from 1.6 to 160 K by a HP4155A semiconductor parameter analyzer. The current self-oscillations were recorded by a HP54600A digital oscilloscope. A typical $I(U)$ curve of the SL sample studied at low temperature is shown in Fig. 1. Three sequential resonance tunneling plateaus are observed with a series of sawtooth-like current branches correspond-

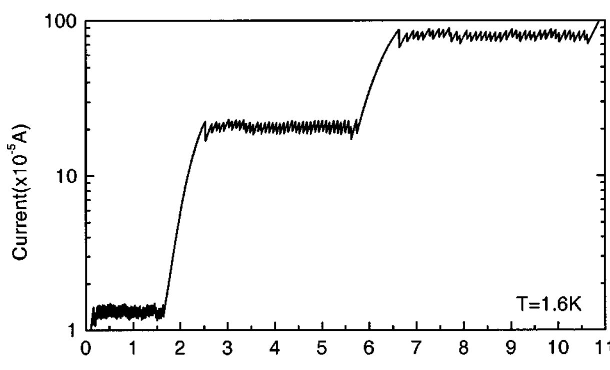

FIG. 1. Typical $I(U)$ curve measured at 1.6 K showing the three current plateaus.

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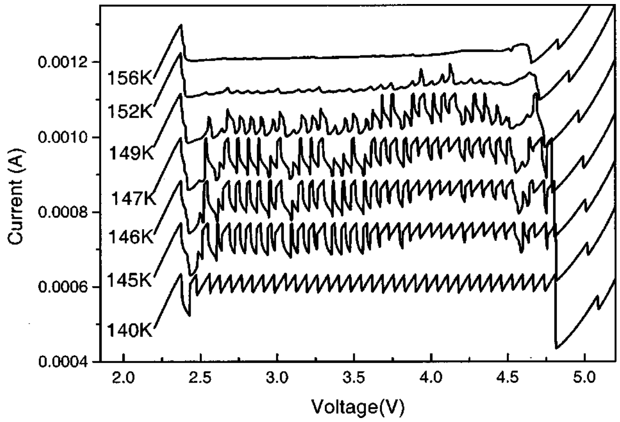

FIG. 2. $I(U)$ curves measured at different temperatures indicated showing the transition process from static to dynamic EFD formation for the second current plateau. Curves are offset for clarity.

ing to static EFD formation. In this study, we focus on the second plateau where low-field domains, in which electrons tunnel from the ground state in one well to the first excited state in the next, coexist with high-field domains in which tunneling is from the ground state to the second excited state. $I(U)$ characteristics exhibit on each plateau a series of 40 sawtooth-like current branches. When the current jumps from one branch to the next, the charge layer at the domain boundary moves from one well to the adjacent well.

The transition process from static to dynamic EFD formation caused by increasing the sample temperature is shown in Fig. 2. At $T=140$ K, the $I(U)$ of the SL exhibits a series of sawtooth-like current branches on the plateau corresponding to static EFD formation. At $T=156$ K, the sawtooth-like branches disappear, a flat current plateau is observed in the $I(U)$, and the current self-oscillations are observed under dc biases across the whole plateau indicating the dynamic EFD formation. During this transition process and at intermediate temperatures, a phenomenon is observed: As is more clearly shown in Fig. 3, which is an enlargement of Fig. 2, a dynamic dc voltage band (indicated by the open squares in Fig. 3) emerges from each sawtooth-like current branch at the beginning of the transition process (see $I(U)$ curve at $T=145$ K in Fig. 3), within this band current self-

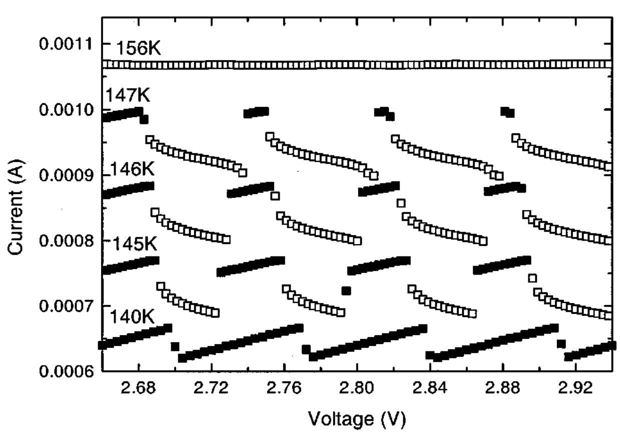

FIG. 3. Enlargements of Fig. 2 show the detailed development of the dynamic voltage band as a function of temperature. Open squares indicate dynamic regions while solid squares indicate static regions. Curves are offset for clarity.

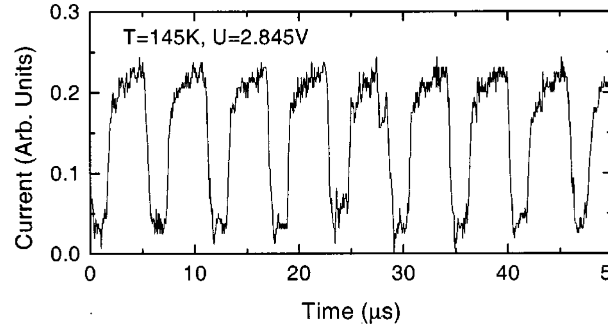

FIG. 4. Measured periodic time dependence of the current at $T=145$ K and $U=2.845$ V, showing the so-called current self-oscillation or dynamic EFD formation.

oscillations or dynamic EFD formation are observed. These dynamic dc voltage bands expand towards the higher-voltage side within each sawtooth-like current branch, squeeze out the static regions (indicated by the solid squares in Fig. 3) in which the static EFDs are formed, and join up together to turn the whole plateau into dynamic EFD formation as the temperature increases. Figure 4 shows an example of the measured periodic time dependence of the current with $T=145$ K and applied dc bias $U=2.845$ V within a dynamic voltage band.

These results can be understood in terms of the general analysis of instabilities and oscillations of the sequential tunneling current in a SL given by Wang and Niu.[11] They have derived general conditions for the stability of the current through a superlattice in which the $I(V)$ characteristic of each tunneling barrier (V being the bias across a single barrier) has a region of NDR. They show that as long as the absolute magnitude of the NDR of one barrier does not exceed the sum of the positive differential resistance (PDR) of the remaining barriers, static EFDs can form. If this condition is not met, the EFDs are unstable and current self-oscillation occurs. Increasing the sample temperature enhances the inelastic scattering through the barrier, increasing the valley current in the $I(V)$ and broadening the resonant tunneling peak so as to reduce the tunneling peak current. As a result, the magnitude of the NDR increases with increasing sample temperature and produces the transition from static to dynamic EFD formation. In this general analysis it is also predicted that the current self-oscillations, associated with the dynamic EFD formation, occur initially within a certain dc voltage range (or voltage band) on each sawtooth-like current branch. Therefore, a series of dynamic voltage bands is formed across the plateau. The dynamic voltage bandwidth is increased with increasing the magnitude of the NDR. While the results of Ref. 11 are general, they are most easily made quantitative by considering a highly idealized model of a SL with $N-1$ wells separated by N barriers. We assume that the tunneling current of each barrier between any two neighboring wells is given by the same piecewise $I(V)$ characteristic shown in Fig. 5.

The three regions of the characteristic have slopes α, $-\beta$, and α, respectively. The meanings of F_1, F_2, Δf, and ΔF are indicated in Fig. 5. Static EFD formation corresponds to k barriers being in the high-field region (domain) and $N-k$ in the low field, where $1 \leqslant k \leqslant N$. The model accounts for the sawtooth-like shape of the SL's $I(U)$ charac-

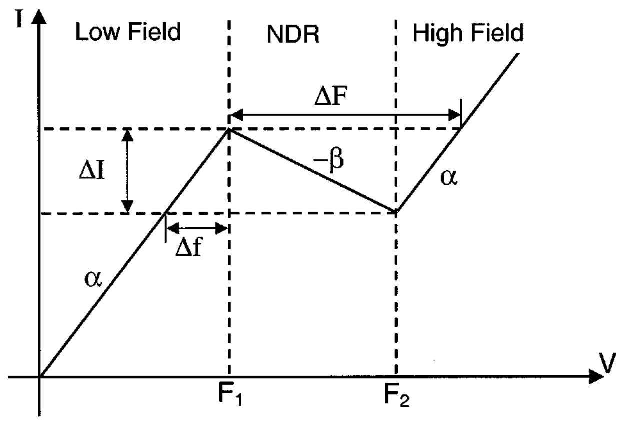

FIG. 5. Piecewise linear $I(V)$ curve where V is the bias across a single barrier. Low-field and high-field regions have the same slope α. NDR region has the negative differential resistance $-1/\beta$.

teristics in the regime of static EFD formation.[9] The current discontinuities in $I(U)$ occur when the external bias U is equal to $NF_1+(k-1)\Delta F$ corresponding to the EFD boundary moves from one well to the adjacent one. Within each sawtooth-like current branch, i.e., for $NF_1+(k-1)\Delta F<U<NF_1+k\Delta F$, the current increases with increasing U. It has been shown in Ref. 11 that EFDs are stable as long as $\Delta F/\Delta f<N$. However, if $\Delta F/\Delta f>N$, corresponding to large NDR, unstable EFD (current self-oscillation) can occur. In this case, within each sawtooth-like current branch the bias U is divided into two regions: (a) $NF_1+(k-1)\Delta F<U<NF_1+k\Delta F-N\Delta f$, where the general conditions for the stability of the current through a superlattice mentioned above is not met. Current self-oscillations or dynamic EFD formation occur to form a dynamic dc voltage band. (b) $NF_1+k\Delta F-N\Delta f<U<NF_1+k\Delta F$, where the general conditions for the stability of the current through a superlattice mentioned above is met. Static EFD formation is then observed. In other words, within each sawtooth-like current branch a dynamic voltage band emerges while the NDR is large so that $\Delta F/\Delta f>N$. As the NDR is further increased, the dynamic region is extended to the high-voltage side on the branch and the static region is reduced. Thus, the model explains the experimental observation described above. Experimentally, the dynamic voltage band is found not to emerge in each current branch simultaneously, indicating that the $I(V)$ of each barrier is, in fact, different across the SL. This complicates the analysis without altering the qualitative conclusions.

In conclusion, the observed dynamic dc voltage band emerging from each sawtooth-like branch in the transition process from static to dynamic EFD formation caused by increasing the sample temperature is explained in terms of varying the $I(V)$ characteristic of a single barrier in a superlattice made up of N such barriers. As the $I(V)$ changes, EFD formation changes from static to dynamic. The dynamic EFD formation occurs initially within a certain dc voltage range on each sawtooth-like branch. The dynamic voltage bandwidth is increased with increasing the magnitude of the NDR.

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[1] The applied electric-field distribution across the superlattice is not uniform and is broken up into different regions, which are called electric-field domains. Static electric-field domain formation corresponds to the stable domain boundary, while dynamic electric-field domain formation corresponds to the unstable domain boundary.

[2] R. Merlin, S. H. Kwok, T. B. Norris, H. T. Grahn, K. Ploog, L. L. Bonilla, J. Galan, J. A. Cuesta, F. C. Martinez, and J. Moleara, in *Proceedings of the 22nd International Conference on the Physics of Semiconductors*, edited by D. J. Lockwood (World Scientific, Singapore, 1995), Vol. 2, p. 1039.
[3] H. T. Grahn, J. Kastrup, K. Ploog, L. L. Bonilla, J. Galan, M. Kindelan, and M. Moscoso, Jpn. J. Appl. Phys., Part 1 **34**, 4526 (1995).
[4] B. Sun, D. Jiang, and X. Wang, Semicond. Sci. Technol. **12**, 401 (1997).
[5] J. Kastrup, R. Hey, K. H. Ploog, H. T. Grahn, L. L. Bonilla, M. Kindelan, M. Moscoso, A. Wacker, and J. Galan, Phys. Rev. B **55**, 2476 (1997).
[6] N. Ohtani, N. Egami, H. T. Grahn, K. Ploog, and L. L. Bonilla, Phys. Rev. B **58**, R7528 (1998).
[7] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974); L. Esaki and L. L. Chang, Phys. Rev. Lett. **8**, 496 (1974).
[8] H. T. Grahn, R. J. Hang, W. Muller, and K. Ploog, Phys. Rev. Lett. **67**, 1618 (1991).
[9] J. Wang, B. Sun, X. Wang, and H. Wang, Solid State Commun. (in press).
[10] Negative differential resistance means the current decreases as applied voltage increases.
[11] X. R. Wang and Q. Niu, Phys. Rev. B **59**, R12755 (1999).
[12] The dynamic voltage bandwidth is defined as the voltage range in which the current oscillates with time at a fixed dc bias.