Magnetic-field effects on undriven chaos in a weakly coupled GaAs/AlAs superlattice

K. J. Luo,[a] K.-J. Friedland, H. T. Grahn,[b] and K. H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5–7, 10117 Berlin, Germany

(Received 17 January 2000; accepted for publication 21 March 2000)

We have investigated the effect of a perpendicular magnetic field on the spontaneous current oscillations in a weakly coupled GaAs/AlAs superlattice. At zero magnetic field, voltage regions of periodic as well as chaotic oscillations are observed. With increasing magnetic field B, the voltage regions for chaotic oscillations become larger and those for periodic oscillations smaller. At $B=9$ T, the whole voltage range consists of chaotic oscillations. At the same time, the time-averaged current–voltage characteristic hardly changes. The experimental observations demonstrate that the quantization by the perpendicular magnetic field results in an equalization of the sequential resonant tunneling process over the whole superlattice, suppressing scattering effects due to disorder. © *2000 American Institute of Physics.* [S0003-6951(00)03120-X]

Resonant tunneling between different subbands in weakly coupled superlattices (SLs) can result in several regions of negative differential velocity (NDV) in the drift-velocity versus electric-field characteristics.[1–3] If the applied electric field happens to be in the NDV region, carriers will accumulate in one of the quantum wells, forming a space-charge layer. As a result, electric-field domains are created, resulting in several current plateaus in the corresponding current–voltage ($I-V$) characteristic.[3,4] Each current plateau is associated with one NDV region. If the carrier density is sufficiently large, static domains are formed. In this case, the electric-field distribution inside the SL breaks up into two regions of constant field, which are separated by a space-charge layer called the domain boundary. The corresponding $I-V$ characteristic exhibits branch-like structures, which are due to the discontinuous motion of the domain boundary through the SL.[1–3] However, if the doping density is below a critical value, the domain formation becomes unstable, resulting in spontaneous current oscillations. In this case, even for a fixed direct current (dc) bias, the domain boundary will move periodically through the SL in a recycling motion.[4] At the same time, the current plateau in the time-averaged $I-V$ characteristics loses its branch-like structure.

Self-sustained, periodic current oscillations have been experimentally observed[4,5] and also obtained in theoretical simulations[1,2,4] for doped SLs. Recently, spontaneous chaotic oscillations (undriven chaos) have also been observed experimentally.[6] When undriven chaos appears, the current plateau shows neither the completely flat behavior nor the regular branch-like structures, but exhibits some local regions of negative differential conductivity (NDC). The voltage regions of undriven chaos decrease with increasing temperature and completely disappear above a certain temperature.[7] The origin of undriven chaos in SLs is still unclear, since the theoretical simulations usually show only periodic oscillations.

In this letter, the effect of a perpendicular magnetic field on the spontaneous current oscillations is experimentally investigated for a weakly coupled GaAs/AlAs SL. Two current plateaus are present in the time-averaged $I-V$ characteristics. Within the first plateau, branch-like structures are observed, indicating the formation of static electric-field domains. However, in the second plateau, the domain formation is unstable. Periodic as well as chaotic self-sustained current oscillations are observed. With increasing magnetic field, the voltage ranges for the undriven chaotic oscillations increase. At the same time, the periodic windows become smaller. At $B=9$ T, almost the whole voltage range is covered by chaotic oscillations. We interpret the results as an equalization of the local transport process between two adjacent wells over the whole SL structure, resulting in a suppression of any disorder.

The investigated sample is a 40 period, weakly coupled SL, consisting of 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 $3.0\times10^{17}\,\mathrm{cm}^{-3}$. 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 by cooling the sample to 1.5 K in pumped He.[4] The magnetic field B is generated by a superconducting magnet with a maximum field strength of 9 T. Both the electric and the magnetic field are applied perpendicular to the SL layers. The time-averaged $I-V$ characteristics are recorded with a Keithley SMU 236. The power spectra of the spontaneous current oscillations are detected with an Advantest R3361 spectrum analyzer with a frequency resolution of 10 kHz using high-frequency coaxial cables with a nominal bandwidth of 20 GHz.

Figure 1 shows time-averaged $I-V$ characteristics recorded at several magnetic fields. In all cases, two current plateaus are observed. At $B=0$ T, branch-like structures separated by a current discontinuity are present within the first plateau of the $I-V$ characteristics (cf. the left hand side of Fig. 1), demonstrating the formation of static domains. In this plateau, the field strength of the low-field domain is related to the resonant alignment of the first subbands in

[a]Present address: Department of Physics, Northwestern University, Evanston, IL 60208.
[b]Electronic mail: htg@pdi-berlin.de

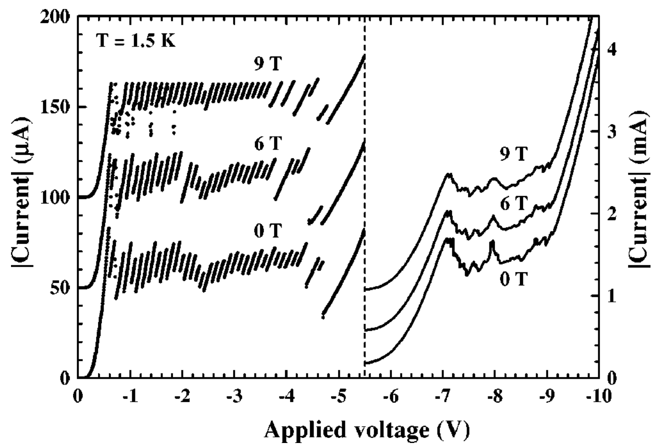

FIG. 1. Time-averaged $I-V$ characteristics recorded at 1.5 K for $B=0$, 6, and 9 T. The traces for voltages between 0 and -5.5 V (-5.5 and -10 V) recorded at 6 and 9 T have been shifted upward by 50 and 100 μA (0.5 and 1.0 mA), respectively.

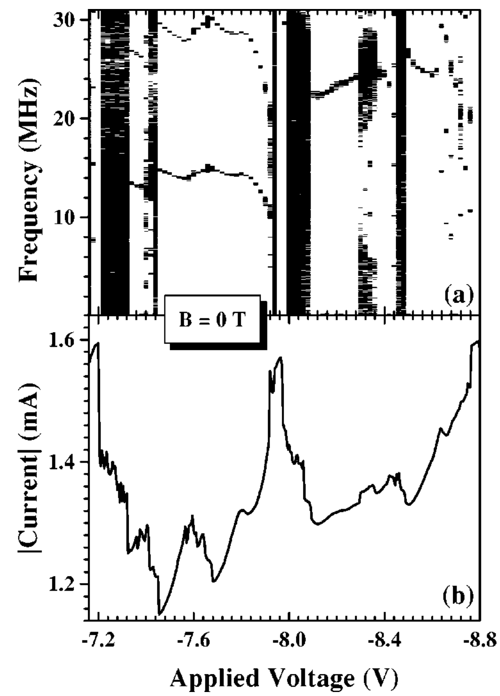

FIG. 2. Power spectra of the self-sustained oscillations (a) vs applied voltage and time-averaged $I-V$ characteristic (b) recorded at $B=0$ T.

adjacent wells, while the field strength of the high-field domain corresponds to resonant tunneling from the first into the second subband in adjacent wells.[4] The second plateau, shown on the right hand side of Fig. 1, does not show the typical branch-like structure of static domain formation. In this voltage range, the sample exhibits self-sustained current oscillations.[4] In this current plateau, the low-field domain is related to resonant tunneling between the first and second subband, while the high-field domain is connected with resonant transfer between the first and the third subband or the X level in the AlAs barrier.[4]

The magnetic field influences the $I-V$ characteristics of the first and second plateau in different ways. In the first plateau, where the domain formation is static, all current branches are well defined and separated by a current discontinuity. While the maximum current and the voltage spacing of the branches become more and more regular with increasing magnetic field as reported in Ref. 8, some branches at very small applied voltages gradually break up, e.g., the first branch at $B=6$ and 9 T. As shown previously, the current discontinuity corresponds to the period-by-period discontinuous motion of the domain boundary through the SL.[2,3] In the second plateau of the $I-V$ characteristics on the right hand side of Fig. 1, the effect of the magnetic field is much less pronounced. The sharp peak observed at $B=0$ T just below -8 V becomes smoother with increasing magnetic field. Apart from these small changes, the effect of the perpendicular magnetic field on the time-averaged $I-V$ characteristics is negligible to that on the frequency spectra of the spontaneous current oscillations in the second plateau of the $I-V$ characteristics, which we present in the following.

Figure 2(a) shows the power spectra of the current oscillations and Fig. 2(b) the corresponding $I-V$ characteristics recorded at zero magnetic field of the second plateau. Current oscillations are observed between -7.16 and -8.78 V, except in a very narrow voltage window from -7.18 to -7.22 V. Chaotic and periodic oscillations appear alternately with increasing dc bias. In the periodic windows, the power spectra consist of a discrete set of frequency peaks, which can be assigned to a fundamental frequency and its higher harmonics. In the chaotic windows, the power spectra spread over the whole frequency range. At $B=0$ T, the chaotic windows appear to be correlated with local regions of NDC in the time-averaged $I-V$ characteristic in Fig. 2(b), while the periodic windows mostly occur in regions of positive differential conductivity (PDC).

For periodic oscillations, the motion of the charge accumulation layer consists of a recycling motion inside the SL, i.e., a new domain boundary appears inside the SL before the old one disappears near the contact. The low-field and high-field domain are still well developed, although their lengths and field strengths are also periodically oscillating due to the recycling motion of the domain boundary. The oscillation of the length of the two domains has been demonstrated in the theoretical simulations[1–4] and also observed experimentally using time-resolved photoluminescence spectroscopy.[5] If the low- and high-field domains are not well established, the charge accumulation layer will be damped out, before it is fully developed. At the same time, a new accumulation layer can be generated due to the presence of the local NDC region. In this way, not necessarily a single domain boundary, but several space-charge layers can be present simultaneously inside the SL. If these space-charge layers are randomly generated and annihilated, chaotic oscillations can appear. The random appearance and disappearance of space-charge layers has been theoretically shown to account for the presence of driven chaos in such SLs.[9]

When the magnetic field is turned on, the width of the chaotic windows increases as shown for $B=6$ T in Fig. 3(a), i.e., for some voltages periodic oscillations are transformed into chaotic oscillations. Current oscillations can now be observed over the whole voltage range from -7.16 to -8.80 V, i.e., the static window between -7.18 and -7.22 V has disappeared. With further increase of the magnetic field to 9 T as shown in Fig. 4(a), the chaotic windows become very wide, covering almost the whole voltage region, where os-

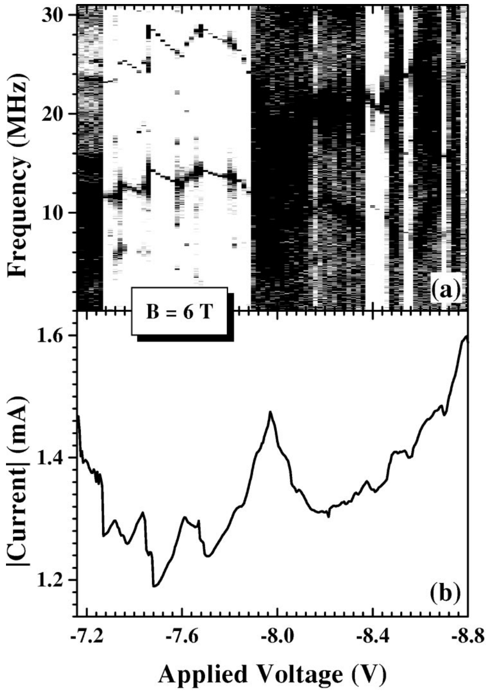

FIG. 3. Power spectra of the self-sustained oscillations (a) vs applied voltage and time-averaged $I-V$ characteristic (b) recorded at $B=6$ T.

cillations are observed. When the magnetic field is turned on, the chaotic oscillations are not confined to the NDC regions in the corresponding time-averaged $I-V$ characteristic, but they also appear in the PDC regions.

The effect of the magnetic field on the static domains has been described in Ref. 8. The increased regularity of the branch spacing and the maximum current has been attributed to a reduction of scattering effects by disorder in the presence of a perpendicular magnetic field due to the resulting reduction of phase space. If we apply this result to the development of undriven chaos with increasing magnetic field, we have to conclude that the suppression of scattering effects due to disorder favors the presence of undriven chaos and a uniformity of its presence over the whole voltage range. The existence of undriven chaos is probably due to the fact that the time scale of the sequential tunneling process is not infinitesimally small. For a finite value, this time scale could act as a driving frequency, which creates the observed undriven, i.e., externally undriven, chaotic behavior. Scattering effects due to disorder seem to suppress this undriven chaos for most applied voltages at zero magnetic field. However, for a magnetic field of 9 T, which results in a strong quantization of all energy states, the underlying transport process for all periods of the SL becomes more similar so that only one type of current oscillations remains. The interesting fact is that in this limit the undriven chaos dominates over the periodic oscillations.

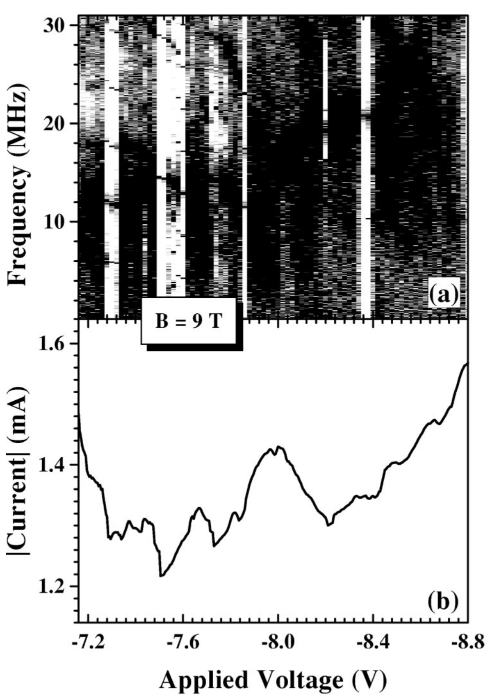

FIG. 4. Power spectra of the self-sustained oscillations (a) vs applied voltage and time-averaged $I-V$ characteristic (b) recorded at $B=9$ T.

The influence of the magnetic field may also be interpreted due to a potential and therefore charge rearrangement by a crossing of the quasi-Fermi level from one Landau level to another at the domain boundary. This potential redistribution can result in an additional time scale, which as earlier interacts with the intrinsic time scale of the current oscillations therefore producing more and more undriven chaotic oscillation regions.

In summary, the effect of a perpendicular magnetic field on spontaneous current oscillations has been studied in a weakly coupled SL. When the magnetic field is zero, periodic as well as chaotic oscillations are observed in the second plateau of the time-averaged $I-V$ characteristics. With increasing magnetic field, the chaotic windows become wider and wider. At $B=9$ T, almost the whole oscillatory regime exhibits chaotic oscillations. We attribute this observation to an equalization of the transport process over the whole SL resulting in a suppression of any disorder effects between different periods. The undriven chaos is probably generated by the presence of the finite time scale of the sequential resonant tunneling process.

The authors would like to thank A. Fischer for sample growth, and H. Kostial and E. Wiebicke for sample structuring. Partial support of the Deutsche Forschungsgemeinschaft within the framework of Sfb 296 is gratefully acknowledged.

[1] L. L. Bonilla, in *Nonlinear Dynamics and Pattern Formation in Semiconductors and Devices*, edited by F.-J. Niedernostheide (Springer, Berlin, 1995), Chap. 1.
[2] A. Wacker, in *Theory of Transport Properties of Semiconductor Nanostructures*, edited by E. Schöll (Chapman and Hall, London, 1998), Chap. 10.
[3] H. T. Grahn, in *Hot Electrons in Semiconductors, Physics and Devices*, edited by N. Balkan (Clarendon, Oxford, 1998), pp. 357–382.
[4] J. Kastrup, R. Hey, K. H. Ploog, H. T. Grahn, L. L. Bonilla, M. Kindelan, M. Moscoso, A. Wacker, and J. Galán, Phys. Rev. B **55**, 2476 (1997).
[5] H. T. Grahn, J. Kastrup, K. Ploog, L. L. Bonilla, J. Galán, M. Kindelan, and M. Moscoso, Jpn. J. Appl. Phys., Part 1 **34**, 4526 (1995).
[6] Y. Zhang, J. Kastrup, R. Klann, K. H. Ploog, and H. T. Grahn, Phys. Rev. Lett. **77**, 3001 (1996).
[7] Y. Zhang, R. Klann, H. T. Grahn, and K. H. Ploog, Superlattices Microstruct. **21**, 565 (1997).
[8] K. J. Luo, K.-J. Friedland, H. T. Grahn, and K. H. Ploog, Phys. Rev. B **61**, 4477 (2000).
[9] O. M. Bulashenko, M. J. García, and L. L. Bonilla, Phys. Rev. B **53**, 10 008 (1996).