AIP Applied Physics Letters

Spontaneous quasi-periodic current self-oscillations in a weakly coupled GaAs/(Al,Ga)As superlattice at room temperature

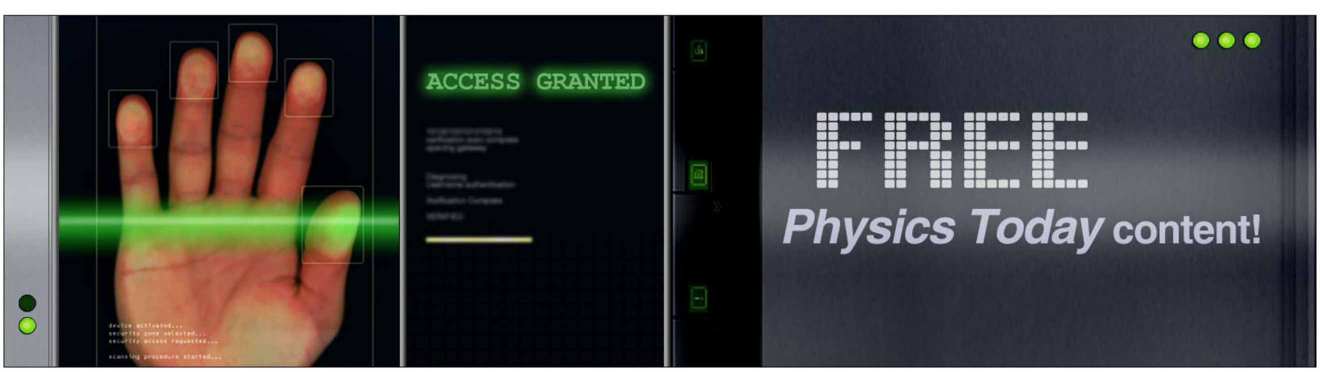
Yuyang Huang, Wen Li, Wenquan Ma, Hua Qin, Holger T. Grahn et al.

Citation: Appl. Phys. Lett. **102**, 242107 (2013); doi: 10.1063/1.4811358
View online: http://dx.doi.org/10.1063/1.4811358
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v102/i24
Published by the AIP Publishing LLC.

Additional information on Appl. Phys. Lett.

Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors

ADVERTISEMENT



Downloaded 19 Jun 2013 to 62.141.165.1. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions

Spontaneous quasi-periodic current self-oscillations in a weakly coupled GaAs/(Al,Ga)As superlattice at room temperature

Yuyang Huang,[1] Wen Li,[1] Wenquan Ma,[2] Hua Qin,[1] Holger T. Grahn,[3] and Yaohui Zhang[1,a)]
[1]*Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, No. 398, Ruoshui Rd, 215123 Suzhou, China*
[2]*Institute of Semiconductors, Chinese Academy of Sciences, No. 35, Qinghua East Rd, 100083 Beijing, China*
[3]*Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5–7, 10117 Berlin, Germany*

(Received 16 May 2013; accepted 28 May 2013; published online 19 June 2013)

We have experimentally observed spontaneous quasi-periodic current self-oscillations at room temperature in a doped, weakly coupled GaAs/(Al,Ga)As superlattice (SL) with 50 periods, 7 nm well width, and 4 nm barrier width. The mole fraction of the aluminum in the barrier has been chosen to be 0.45 so that the direct barrier at the Γ point is as high as possible and thermal carrier leakage through the X valley is as small as possible. A spectral analysis of the current self-oscillations, which are observed under DC voltage bias alone, demonstrates that spontaneous quasi-periodic oscillation modes coexist with periodic ones. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4811358]

A semiconductor superlattice (SL) represents an almost ideal one-dimensional nonlinear dynamical system with a large number of degrees of freedom. Growth imperfections and various fluctuations of the layer thicknesses, electron density, energy levels, and inter-well coupling transform a semiconductor SL into a complex nonlinear system, in which the electron transport is strongly dissipative.[1,2] In the last two decades, extensive investigations have been carried out in this field,[3–6] which are summarized in Ref. 7. A great richness of nonlinear transport behavior has been observed, including the formation of stationary electric-field domains,[8] self-sustained current oscillations,[9] and even chaos.[10] The strong nonlinearity in a doped, weakly coupled semiconductor SL originates from sequential resonant tunneling between adjacent quantum wells. The oscillatory behavior is attributed to the localized, oscillatory motion of the domain boundary, which separates the high from the low electric-field domain.[11] The resulting dynamical behavior depends on the SL configuration, doping density, boundary condition, external bias, ambient temperature, etc. Very recently, spontaneous chaotic current oscillations at room temperature[12] and the noise-induced current switching[13] have been reported in weakly coupled GaAs/(Al,Ga)As SLs.

Among the many studies on vertical transport in weakly coupled semiconductor SLs, most of the investigations have been performed at low temperatures. Only very few experimental results have been reported that were obtained at room temperature.[12,14,15] Usually, the thermally activated background current density is probably too high to realize current oscillations related to sequential resonant tunneling at room temperature. In this study, we have chosen the Al mole fraction of the barrier material to be 0.45 so that the direct barrier at the Γ point of the conduction band is as high as possible and thermal carrier leakage through the X valley of the conduction band is as small as possible. At the same time, only the central part of the GaAs quantum well is doped so that the interfaces between the wells and barriers remain rather undoped in order to reduce interface states.

In this letter, we report on the experimental observation of spontaneous periodic and quasi-periodic current oscillations in a doped, weakly coupled GaAs/(Al,Ga)As SL at room temperature. For particular bias voltages, we detect periodic current oscillations corresponding to an oscillation mode with a single frequency. When the DC bias is varied, the frequency spectra exhibit in addition to the main oscillation peak several side lobes, which correspond to a quasi-periodic oscillation mode. The number and intensity of the side lobes vary as the DC bias is changed. A spectral analysis shows that both periodic and quasi-periodic oscillation modes exist in this doped, weakly coupled SL, but at different applied voltages. Two oscillation modes, the dipole-motion mode through the whole SL and the well-to-well hopping mode confined to a few periods of the SL, may both exist. Their interaction would then result in the observed oscillation dynamics.

The investigated sample consists of a doped, weakly coupled SL with 50 periods, 7.0 nm thick GaAs wells, and 4.0 nm thick $Al_{0.45}Ga_{0.55}As$ barriers grown by molecular beam epitaxy on an *n*-GaAs(001) substrate in a Veeco system. Based on our previous research,[10,12,16] the central 3.0 nm of each well are doped with Si at $2 \times 10^{17}\,cm^{-3}$, while the remaining part of each well is undoped to reduce the interface state density. With an Al mole fraction of 0.45 in the barrier and a barrier width of 4.0 nm, the resonant coupling between adjacent wells remains in the weak coupling regime. The SL is sandwiched between two highly Si-doped (Al,Ga)As contact layers forming an n^+-n-n^+ diode. Square and circular mesa structures with a side length and diameter, respectively, of 120 μm have been etched by $H_2SO_4/H_2O_2/H_2O$. Subsequently, Ohmic contacts are formed by electron beam evaporation of AuGe/Ni/Au (35/10/300 nm) followed by rapid thermal annealing in a nitrogen atmosphere at 415 °C for 35 s. The sample is mounted into a package with electromagnetic shielding and connected to the source by high-frequency cables with SMA connectors. All experimental data are recorded at room temperature without any cryostat or cooling system. The DC bias is applied using an

[a)]Electronic mail: yhzhang2006@sinano.ac.cn

 © 2013 AIP Publishing LLC

Downloaded 19 Jun 2013 to 62.141.165.1. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions

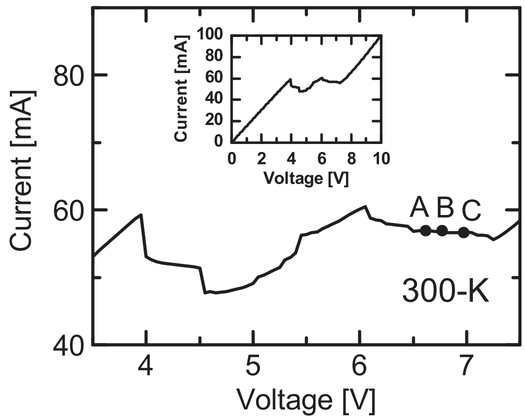


FIG. 1. Plateau region of the *I-V* characteristics of the investigated weakly coupled GaAs/(Al,Ga)As SL. The inset displays the whole bias range. The operating points corresponding to periodic, intermediate, and quasi-periodic oscillations are marked as A, B, and C, respectively.

Agilent 33220A function generator. The time-domain current oscillations are recorded with an Agilent MSO6102A oscilloscope with 1 GHz bandwidth. The frequency spectra are recorded with an Agilent N9020A frequency analyzer.

A typical *I-V* characteristics of the GaAs/$Al_{0.45}Ga_{0.55}As$ SL is shown in Fig. 1. A plateau-like region, which originates from the sequential resonant tunneling between adjacent wells, is clearly visible. When a DC bias is applied inside the plateau region, spontaneous current oscillations are observed. The self-oscillations of three typical operation points, which correspond to the periodic, intermediate, and quasi-periodic self-oscillations, are shown in the time and frequency domain in Figs. 2(a) and 2(b), respectively. The corresponding operating points are marked as A, B, and C in Fig. 1. When the DC bias is set at 6.602 V (point A), the current self-oscillations are periodic. In the frequency domain, sharp peaks appear only at the fundamental frequency and its higher harmonics. Correspondingly, the waveform in the time domain is quite regular. In contrast, when the DC bias is slightly increased to 6.762 V (point B), the self-oscillations turn into an intermediate state. In the frequency domain, several side lobes begin to appear around the fundamental frequency peak and its harmonics. The regularity of the oscillations in the time domain is somewhat reduced for this bias value. When the DC bias is further increased to 6.951 V (point C), more side lobes develop, and their strength increases. At the same time, the regularity of the oscillations in the time domain is further reduced. The SL enters a so-called *quasi-periodic* state.

To obtain spontaneous current self-oscillations at room temperature, one key factor is to increase the confinement of the quantum states involved in the resonant tunneling process. In our design, we only dope the central part of the quantum well layer in order to minimize the density of interface states. In addition, we use an Al mole fraction of 0.45 in the barrier layer so that the direct barrier at the Γ point is as high as possible and thermal carrier leakage through the X valley of the conduction band is minimized. In this case, the first energy level of the X point is above the first level of the Γ point. Thus, the current leakage through the X valley is dramatically reduced. This design allows for spontaneous chaotic current self-oscillations at room temperature.[12]

Physically, the observed periodic and quasi-periodic current self-oscillations may originate from the interplay between the two intrinsic oscillation modes of the SL: the collective dipole motion mode through the whole SL and the well-to-well hopping mode, which is confined to a few SL periods. The former mode is related to the creation, motion, and recycling of the dipoles from the emitter to the collector, while the latter mode is associated with the well-to-well hopping of the domain boundary within a small part of the SL.[9,11,17,18] A similar mechanism has also been discussed, when the presence of noise induces a global change in the dynamics of the system forcing stationary fronts to move through the entire superlattice.[19] When the DC bias is below a certain threshold, only the collective dipole motion mode is activated. The dipoles are generated in the emitter, move toward the collector, and disappear in a regular way. Thus, the SL enters a periodic state with a well-defined fundamental frequency and exhibits a periodic oscillation characteristics. When the DC bias is increased to be larger than a threshold value, the well-to-well hopping mode is activated. In this mode, the dipole hops over several adjacent periods of the SL with a specific

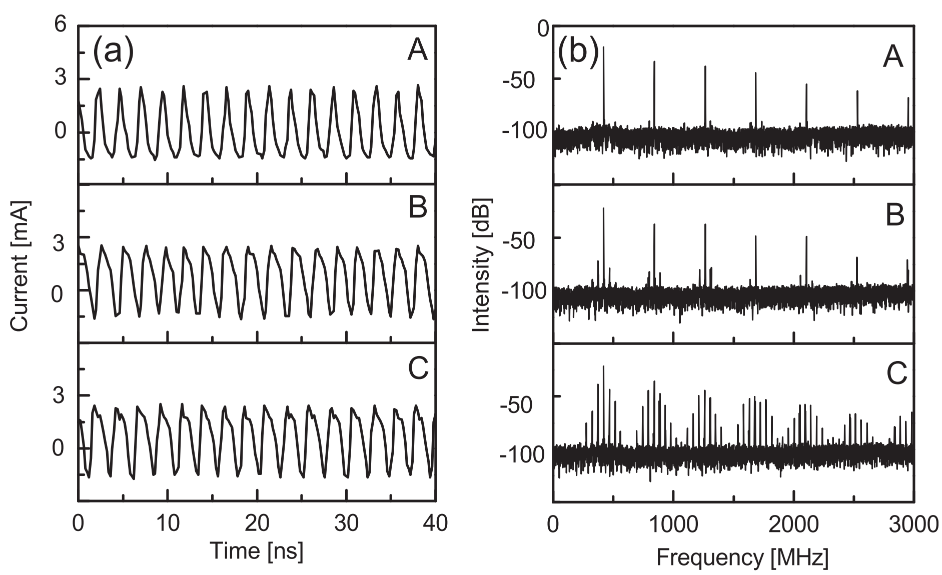


FIG. 2. Periodic (A), intermediate (B), and quasi-periodic (C) current self-oscillations in the (a) time (only AC component) and (b) frequency domain. The central and bottom parts in each figure are vertically shifted for clarity.

Downloaded 19 Jun 2013 to 62.141.165.1. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions

frequency, resulting in a frequency superposition with the main collective dipole motion mode. Consequently, small side lobes appear around the main oscillation peaks in the frequency spectra. Correspondingly, some irregular spikes appear in the time domain. When the DC bias is further increased, the well-to-well hopping mode of the dipoles becomes stronger. The interaction between the collective dipole motion mode and the well-to-well hopping oscillation mode increases. More side lobes with larger intensity appear. The SL system enters a quasi-periodic oscillation state.

In conclusion, spontaneous quasi-periodic current self-oscillations have been experimentally observed in a 50-period GaAs/$Al_{0.45}Ga_{0.55}As$ [7 nm GaAs/4 nm (Al,Ga)As] SL. The Al mole fraction of the barrier was chosen to be 0.45 in order to maximize the direct barrier and simultaneously to minimize the thermal carrier leakage through the X valley. For certain bias conditions, we detect periodic self-oscillations of the current, which correspond to a harmonic oscillation mode. When the DC bias is varied, several side lobes around the main oscillation peak appear in the frequency spectra, which correspond to a quasi-periodic oscillation mode. The physical mechanism may be related to the interaction of two oscillation modes, namely, the collective dipole motion mode through the whole SL and the well-to-well hopping mode within a few SL periods. This observation opens up the possibility to realize chaos at room temperature, which is currently only possible at liquid nitrogen temperatures. This effect may be used in tunable microwave oscillators and for true random number generators.

This work has been supported by the Department of Science and Technology, Jiangsu Province (BK2010005 and BY20111179), Natural Science Foundation of China (61204093), and Artificial Structure and Quantum Control Laboratory of Shanghai Jiao Tong University (2013).

[1]E. Schöll, *Nonlinear Spatio-Temporal Dynamics and Chaos in Semiconductors* (Cambridge University Press, New York, 2001).
[2]L. L. Bonilla and S. W. Teitsworth, *Nonlinear Wave Methods for Charge Transport* (Wiley-VCH, Berlin, 2010).
[3]L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1970).
[4]R. Tsu and L. Esaki, Appl. Phys. Lett. **19**, 246 (1971).
[5]L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).
[6]F. Capasso, K. Mohammed, and A. Y. Cho, Appl. Phys. Lett. **48**, 478 (1986).
[7]L. L. Bonilla and H. T. Grahn, Rep. Prog. Phys. **68**, 577 (2005).
[8]H. T. Grahn, R. J. Haug, W. Müller, and K. Ploog, Phys. Rev. Lett. **67**, 1618 (1991).
[9]H. Grahn, J. Kastrup, K. Ploog, L. Bonilla, J. Galán, M. Kindelan, and M. Moscoso, Jpn. J. Appl. Phys., Part 1 **34**, 4526 (1995).
[10]Y. H. Zhang, J. Kastrup, R. Klann, K. H. Ploog, and H. T. Grahn, Phys. Rev. Lett. **77**, 3001 (1996).
[11]J. Kastrup, R. Klann, H. T. Grahn, K. Ploog, L. L. Bonilla, J. Galán, M. Kindelan, M. Moscoso, and R. Merlin, Phys. Rev. B **52**, 13761 (1995).
[12]Y. Y. Huang, W. Li, W. Q. Ma, H. Qin, and Y. H. Zhang, Chin. Sci. Bull. **57**, 2070 (2012).
[13]Yu. Bomze, R. Hey, H. T. Grahn, and S. W. Teitsworth, Phys. Rev. Lett. **109**, 026801 (2012).
[14]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).
[15]J. Wu, D. Jiang, and B. Sun, Physica E **4**, 137 (1999).
[16]Y. H. Zhang, X. P. Yang, W. Liu, P. H. Zhang, and D. S. Jiang, Appl. Phys. Lett. **65**, 1148 (1994).
[17]J. Kastrup, F. Prengel, H. T. Grahn, K. Ploog, and E. Schöll, Phys. Rev. B **53**, 1502 (1996).
[18]D. Sánchez, M. Moscoso, L. L. Bonilla, G. Platero, and R. Aguado, Phys. Rev. B **60**, 4489 (1999).
[19]J. Hizanidis, A. Balanov, A. Amann, and E. Schöll, Phys. Rev. Lett. **96**, 244104 (2006).

Downloaded 19 Jun 2013 to 62.141.165.1. This article is copyrighted as indicated in the abstract. Reuse of AIP content is subject to the terms at: http://apl.aip.org/about/rights_and_permissions