ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理
Chinese Physics B

Hydrodynamic simulation of chaotic dynamics in InGaAs oscillator in terahertz region

Wei Feng(冯伟)

Citation: Chin. Phys. B . 2020, 29(4): 047302 . **doi:** 10.1088/1674-1056/ab696f
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Dynamic control of the terahertz rainbow trapping effect based on a silicon-filled graded grating

Shu-Lin Wang(王书林), Lan Ding(丁岚), Wen Xu(徐文)

Chin. Phys. B . 2017, 26(1): 017301 . **doi:** 10.1088/1674-1056/26/1/017301

Design of terahertz beam splitter based on surface plasmon resonance transition

Xiang Liu(刘项), Dong-Xiao Yang(杨冬晓)

Chin. Phys. B . 2016, 25(4): 047301 . **doi:** 10.1088/1674-1056/25/4/047301

Polarization-independent terahertz wave modulator based on graphene-silicon hybrid structure

Liang-Liang Du(杜亮亮), Quan Li(李泉), Shao-Xian Li(李绍限), Fang-Rong Hu(胡放荣), Xian-Ming Xiong(熊显名), Yan-Feng Li(栗岩锋), Wen-Tao Zhang(张文涛), Jia-Guang Han(韩家广)

Chin. Phys. B . 2016, 25(2): 027301 . **doi:** 10.1088/1674-1056/25/2/027301

Spoof surface plasmons resonance effect and tunable electric response of improved metamaterial in the terahertz regime

Wang Yue, Zhang Li-Ying, Mei Jin-Shuo, Zhang Wen-Chao, Tong Yi-Jing

Chin. Phys. B . 2015, 24(12): 127302 . **doi:** 10.1088/1674-1056/24/12/127302

Electrically tunable resonant terahertz transmission in subwavelength hole arrays

Zhang Ying, Liu Ying-Kai, Han Jia-Guang

Chin. Phys. B . 2014, 23(6): 067301 . **doi:** 10.1088/1674-1056/23/6/067301

SPECIAL TOPIC — Terahertz physics

Hydrodynamic simulation of chaotic dynamics in InGaAs oscillator in terahertz region*

Wei Feng(冯伟)†

Department of Physics, Jiangsu University, Zhenjiang 212013, *China*

(Received 12 December 2019; revised manuscript received 3 January 2020; accepted manuscript online 9 January 2020)

Hydrodynamic calculations of the chaotic behaviors in n^+nn^+ $In_{0.53}Ga_{0.47}As$ devices biased in terahertz (THz) electric field have been carried out. Their different transport characteristics have been carefully investigated by tuning the n-region parameters and the applied ac radiation. The oscillatory mode is found to transit between synchronization and chaos, as verified by the first return map. The transitions result from the mixture of the dc induced oscillation and the one driven by the ac radiation. Our findings will give further and thorough understanding of electron transport in $In_{0.53}Ga_{0.47}As$ terahertz oscillator, which is a promising solid-state THz source.

Keywords: terahertz, chaotic, current oscillation

PACS: 73.61.Ey, 73.50.Fq, 85.30.Fg, 85.30.De **DOI:** 10.1088/1674-1056/ab696f

1. Introduction

Devices operating in the THz frequency region have attracted a great deal of attention due to their wide applications, such as security inspection, imaging, and radar.[1–4] Compact and coherent solid-state THz sources working at room temperature are fundamental and important for such applications. Various devices have been investigated theoretically and experimentally as THz sources, from both optical and electronic aspects. As a typical optical device, the quantum cascade laser (QCL) represents an efficient coherent THz source,[5] but its low operating temperature is a major limitation. As typical electronic devices, resonant tunneling diodes (RTDs), silicon complementary metal oxide semiconductors (Si CMOS), hetero-bipolar transistors (HBTs), and high electron-mobility transistors (HEMTs) are being studied intensively as THz sources.[6–8] Besides, negative differential velocity (NDV) oscillators are good candidates as room-temperature THz sources.

Many recent efforts have been devoted to the NDV effect, as originally proposed by Krömer, to generate and amplify the current oscillation.[9] There are two NDV mechanisms. One is the Ridley–Watkins–Hilsum (RWH) mechanism. In a multi-valley semiconductor like GaAs and InGaAs,[10,11] the transfer of carriers into a higher energy state with larger effective mass and lower velocity results in the NDV effect. The other one is the negative effective mass (NEM) mechanism due to the nonparabolic band dispersion like in InN.[12] In a single nonparabolic band, when the electron transits through the inflection point, its effective mass changes sign to be negative, leading to a different NDV effect. Various materials have been explored as NDV THz oscillators.[13,14] In 2007, the first hetero-structure planar Gunn diode based on AlGaAs/GaAs was demonstrated with operating frequency above 100 GHz.[15] However, the frequency of the device, as limited by GaAs's saturation velocity, cannot be increased efficiently to high enough. To overcome this disadvantage, $In_{0.53}Ga_{0.47}As$ layer, which has a good lattice match to the InP substrate, was proposed to replace GaAs. In 2013, the first 164 GHz $In_{0.53}Ga_{0.47}As$ diode was achieved.[16] To increase the frequency further, a submicron $In_{0.53}Ga_{0.47}As$ diode in a planar layout was proposed. Compared to the linear optical and electronic responses in $In_{0.53}Ga_{0.47}As$, which have been extensively studied, fewer investigations are based on nonlinear transport effects. The external radiation on the device is expected to result in complicated transport of electrons and the resulting oscillations are time- and space-dependent. Thus, nonlinear transport effects are very essential and efficient for nonequilibrium optical and electronic processes. They are crucial for a thorough understanding of fundamental properties of the $In_{0.53}Ga_{0.47}As$ oscillator.

In the present work, we apply a hydrodynamic model to investigate nonlinear dynamics in n^+nn^+ $In_{0.53}Ga_{0.47}As$ diode. Although the Monte–Carlo method has been widely used in the theoretical investigations of the lattice-matched $In_{0.53}Ga_{0.47}As$ for Gunn oscillators,[14,17,18] the hydrodynamic model has higher efficiency by exploiting some reasonable approximations. Using the hydrodynamic model, we have previously studied the current self-oscillation in the n^+nn^+ $In_{0.53}Ga_{0.47}As$ diode under dc bias. Here we continue to investigate the chaotic behaviors under THz radiation by care-

*Project supported by the National Natural Science Foundation of China (Grant No. 11604126) and China Scholarship Council (Grant No. 201808695016).

†Corresponding author. E-mail: wfeng@ujs.edu.cn

© 2020 Chinese Physical Society and IOP Publishing Ltd

fully tuning the parameters of dc bias, doping concentration, and intensity of radiation.

2. Hydrodynamic simulation of chaotic dynamics in InGaAS THz oscillator

InGaAs pronounced NDV feature was reported theoretically and experimentally.[11] Figure 1 (a) shows the relation of the drift velocity V_d to applied electric field E. The inset shows the schematic diagram of the n^+nn^+ InGaAs diode.[19] At room temperature, for an doped $In_{0.53}Ga_{0.47}As$ diode ($N_d = 10^{18}$ cm^{-3}), the velocity first increases, reaching a pronounced peak value of 1.93×10^5 m/s at $E = 3.9$ kV/cm, and then decreases, which forms the NDV region. The fitting curve for the V_d–E relation can be expressed as

$$V_d = \frac{0.92E}{1+(E/4.214)^{2.3}}, \tag{1}$$

which is in a very good agreement with the experiment. When the diode is applied with a dc bias, self-current oscillation shows up, as seen in Fig. 1(b). Different dc biases will lead to current oscillations with different frequencies.

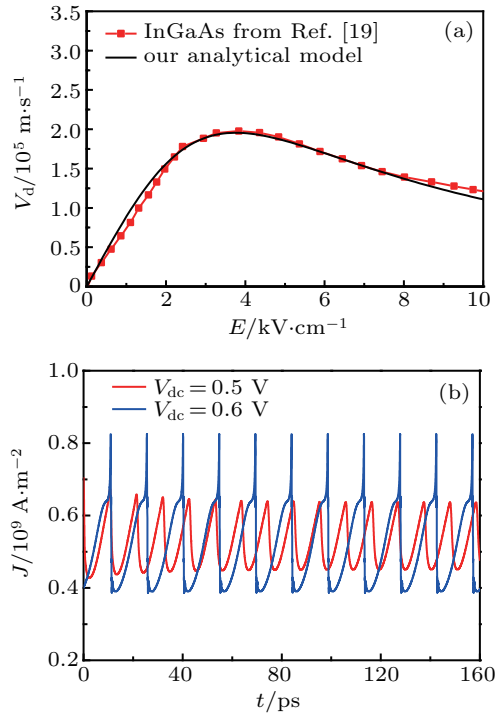


Fig. 1. (a) Fitting V_d–E curve of InGaAs at room temperature in comparison with experiment. (b) Self-current oscillations under two different dc biases.

To get a better understanding of the oscillations in n^+nn^+ InGaAs THz oscillator, we next investigate the oscillatory modes of the diode under the influences of both self-sustained electric field and external THz radiation in the form of

$$E(t) = E_s + E_{ext}, \tag{2}$$

where E_s is the self-sustained electric field, and $E_s = V_{dc}/l$ with V_{dc} the dc bias and l the n region length which is set to be 0.5 μm here. E_{ext} is the external THz radiation expressed as $E_{ext}(t) = V_{ac}\cos(2\pi f_{ac}t)/l$, with ac intensity V_{ac} and frequency f_{ac}. We apply the hydrodynamic equations[20–25] to study the nonlinear dynamics in the $In_{0.53}Ga_{0.47}As$ diode

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial j_n}{\partial x}, \tag{3}$$

$$j_n = q\mu_n\left(\frac{K_BT}{q}\frac{\partial n}{\partial x} + \frac{K_Bn}{q}\frac{\partial T_e}{\partial x} - n\frac{\partial \varphi}{\partial x}\right), \tag{4}$$

$$\frac{\partial (n\varepsilon)}{\partial t} = -\frac{\partial (nS)}{\partial x} - j_n\frac{\partial \varphi}{\partial x} - nW. \tag{5}$$

Here, j_n is the current density, $\mu_n = V_d/E$ is the mobility, ε is the electron energy, S is the energy flow density, and W is the energy loss rate. The electron density n is related to the electrostatic potential φ through the Poisson equation

$$\frac{\partial^2\varphi}{\partial x^2} = -\frac{q}{\varepsilon}(n - N_d), \tag{6}$$

where ε is the static dielectric constant and N_d is the doping concentration. Any small doping inhomogeneity in the NDV region can lead to the formation of domain and oscillations.[20] We assume that there is a slight doping fluctuation near each end of the diode. This fluctuation results in the formation of electric field domain and hence current oscillation. By applying the transient hydrodynamic model to n^+nn^+ $In_{0.53}Ga_{0.47}As$ diodes at room temperature, we carry out the simulation of the time-dependent current density in the diodes, which can be expressed as

$$J(t) = j(z,t) + \varepsilon_s\frac{\partial E(z,t)}{\partial t}. \tag{7}$$

The boundary conditions for the time-dependent and space-dependent electrostatic potential $\varphi(x,t)$ and election density $n(x,t)$ are set to be

$$\varphi(x_L,t) = 0, \quad \varphi(x_R,t) = E(t)l, \tag{8}$$

$$n(x_L,t) = N_d(x_L), \quad n(x_R,t) = N_d(x_R). \tag{9}$$

When both a dc bias V_{dc} and a sinusoidal ac voltage V_{ac} are applied to the InGaAs diode, nonlinear chaotic dynamics are observed to be dependent on many factors, such as V_{dc}, V_{ac}, and f_{ac}. The results are shown in Figs. 2 and 3. Here in the simulations shown in Fig. 2, V_{dc} is 0.5 V and N_d is 5×10^{16} cm^{-3} at room temperature. At $V_{dc} = 0.5$ V, the current oscillates with frequency $f_s = 0.093$ THz. In the simulations, we set the ac frequency as $f_{ac} = G\times f_s \approx 0.15$ THz. The G [$\equiv (1+5)/2 = 1.618\ldots$] is the inverse golden mean, and this ratio is regarded as the most irrational of all irrational numbers and frequently used in nonlinear systems.[26,27] Figure 2(a) shows the Poincaré bifurcation diagram with V_{ac} as the controlling parameter changing from 0 to 0.07 V. When V_{ac} is smaller than 0.055 V, the system exhibits a complicated and chaotic behavior. When increasing the ac amplitude to

be larger than 0.055 V, the system exhibits a periodic behavior. Here we have applied the first return maps to distinguish periodic states from chaotic ones. The first return maps under two specific ac voltages $V_{ac} = 0.012$ V and 0.065 V are shown in Figs. 2(b) and 2(c). The first return maps provide us with a clear picture to distinguish the chaotic and periodic states, where m separate points indicate the system to be m-periodic while infinite random points imply a chaotic system. As shown in Fig. 2 for $V_{ac} = 0.012$ V, there are infinite random points in the first return map, which indicates that the system exhibits a complicated and chaotic behavior. While for $V_{ac} = 0.065$ V, there is only one point in the first return map, which indicates one periodic system.

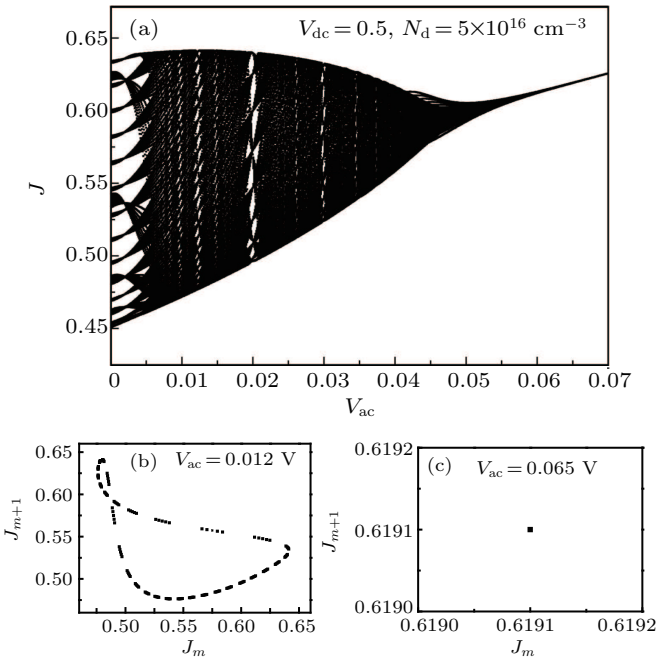


Fig. 2. Nonlinear and dynamic oscillatory modes of $In_{0.53}Ga_{0.47}As$ diode at $V_{dc} = 0.5$ V and $N_d = 5 \times 10^{16}$ cm^{-3}. (a) The bifurcation diagram, (b) the first return map at $V_{ac} = 0.012$ V, and (c) the first return map at $V_{ac} = 0.065$ V.

The effect of the dc voltage on the current has also been considered and simulated. Figure 3 shows the bifurcation diagram and first return maps with $N_d = 5 \times 10^{16}$ cm^{-3} and $V_{dc} = 0.55$ V at room temperature. V_{ac} changes from 0 to 0.12 V. The bifurcation diagram (Fig. 3(a)) shows a different complex nonlinear dynamics from the oscillatory modes in Fig. 2. When V_{ac} is smaller than 0.0662 V, the results have lots of points representing a chaotic state. As V_{ac} is 0.0662 V, a 3-periodic pattern appears abruptly. With V_{ac} further increasing and approaching 0.08 V, the periodic behavior disappears and the solutions become chaotic again. Furthermore, when V_{ac} increases beyond 0.092 V, the system changes to single-periodic. With tuning V_{ac}, the cooperative nonlinear oscillatory mode transits between the chaotic and periodic patterns. In Figs. 3(b) and 3(c), the first return maps for $V_{ac} = 0.04$ V and 0.075 V are displayed, respectively. When $V_{ac} = 0.04$ V, there are infinite random points verifying the chaotic state, while when $V_{ac} = 0.075$ V there are 3 separate points verifying the 3-periodic state. These transitions originate from the competition between the intrinsic self-oscillation and the external THz radiation. For the periodic states, the oscillatory modes are the linear mixture of the external radiation induced oscillations with f_{ac}, while for the chaotic ones, the oscillatory modes result from both intrinsic self-oscillation and the external THz radiation with f_s and f_{ac}.

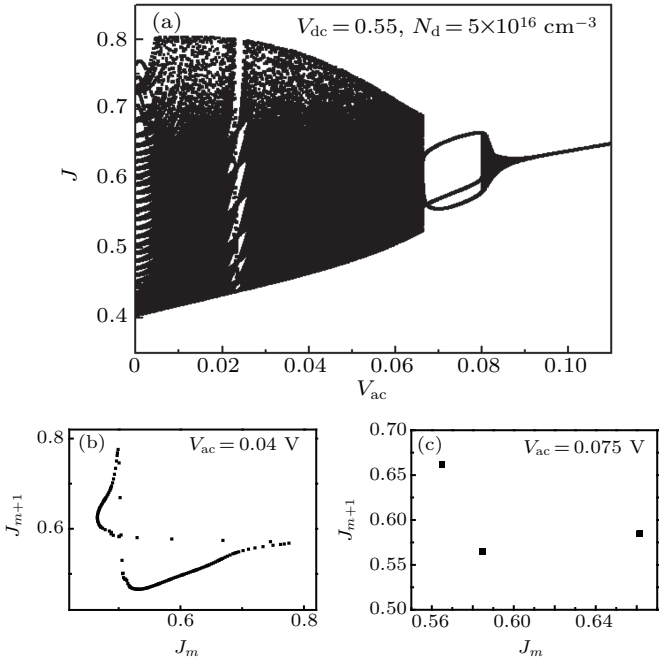


Fig. 3. Nonlinear and dynamic oscillatory modes of $In_{0.53}Ga_{0.47}As$ diode at $V_{dc} = 0.55$ V and $N_d = 5 \times 10^{16}$ cm^{-3}. (a) The bifurcation diagram, (b) the first return map at $V_{ac} = 0.04$ V, (c) the first return map at $V_{ac} = 0.075$ V.

3. Conclusion

To summarize, by applying hydrodynamic equations, we have simulated the nonlinear dynamics in n^+nn^+ $In_{0.53}Ga_{0.47}As$ diodes subjected to both dc and ac signals. The dependence of the cooperative nonlinear oscillatory mode on th edc bias, doping concentration, and ac intensity has been carefully analyzed. The transitions between periodic and chaotic patterns are revealed and originate from the mixture and competition between the intrinsic oscillation and the ac-induced one. Our findings will provide further fundamental understanding of $In_{0.53}Ga_{0.47}As$ diodes, applicable as a promising solid-state source for THz applications.

References

[1] Tonouchi M 2007 *Nat. Photon.* **1** 97
[2] Hangyo M 2015 *Jpn. J. Appl. Phys.* **54** 120101
[3] Yang X, Zhao X, Yang K, Liu Y, Liu Y, Fu W and Luo Y 2016 *Trends Biotechnol.* **34** 810
[4] Woolard D L, Brown E R, Pepper M and Kemp M 2005 *Proc. IEEE* **93** 1722

[5] Zhou K, Li H, Wan W J, Li Z P, Liao X Y and Cao J C 2019 *Appl. Phys. Lett.* **114** 191106
[6] Mao X R, Xie S, Zhu C J, Geng Z X and Chen H D 2018 *AIP Adv.* **8** 065323
[7] Kasagi K, Suzuki S and Asada M 2019 *J. Appl. Phys.* **125** 151601
[8] Samoska L A 2011 *IEEE Trans. Terahertz Sci. Technol.* **1** 9
[9] Krömer H 1958 *Phys. Rev.* **109** 1856
[10] Gunn J B 1963 *Solid State Commun.* **88** 883
[11] Karishy S 2015 *Lith. J. Phys.* **55** 305
[12] Feng W 2012 *Chin. Phys. Lett.* **29** 017304
[13] Kitagawa S 2017 *Jpn. J. Appl. Phys.* **56** 058002
[14] Perez S, Gonzlez T, Pardo D and Mateos J 2008 *J. Appl. Phys.* **103** 094516
[15] Khalid A, Pilgrim N J, Dunn G M, Holland M C and Stanley C R 2007 *IEEE Electron Device Lett.* **28** 849
[16] Khald A, Dunn G M, Macpherson R F, *et al.* 2014 *J. Appl. Phys.* **115** 114502
[17] Choo K Y and Ong D S 2004 *J. Appl. Phys.* **96** 5649
[18] Mookerjea S, Mohata D, Mayer T, Narayanan V and Datta S 2010 *IEEE Electron Device Lett.* **31** 564
[19] Costa J, Peczalski A and Shur M 1989 *J. Appl. Phys.* **65** 5205
[20] Gruzhinskis V, Starikov E and Shiktorov P 1992 *Appl. Phys. Lett.* **61** 1456
[21] Gruzhinskis V, Starikov E, Shiktorov P, Reggiani L and Varani L 1994 *Phys. Rev. B* **49** 13650
[22] Gruzhinskis V, Starikov E and Shiktorov P 1994 *J. Appl. Phys.* **76** 5260
[23] Cao J C and Lei X L 1999 *Phys. Rev. B* **60** 1871
[24] Cao J C and Lei X L 1999 *Phys. Rev. B* **59** 2199
[25] Ziade P, *et al.* 2010 *Semicond. Sci. Technol.* **25** 075012
[26] Zhang Y H, Kastrup J, Klann R, Ploog K H and Grahn H T 1996 *Phys. Rev. Lett.* **77** 3001
[27] Cao J C, Liu H C and Lei X L 2001 *Phys. Rev. B* **63** 115308