SCIENCE CHINA
Technological Sciences

• Article •

August 2015 Vol.58 No.8: 1348–1354
doi: 10.1007/s11431-015-5873-5

Piezotronic transistors in nonlinear circuit: Model and simulation

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Received May 21, 2015; accepted June 12, 2015; published online July 2, 2015

For the materials that simultaneously exhibit piezoelectric and semiconductor properties, such as wurtzite ZnO, GaN and InN, as well as two-dimensional single MoS_2, piezoelectric charges induced by externally applied strain can tune/control carrier transport at a metal-semiconductor contact or semiconductor junction, which is named piezotronic effect. Metal-semiconductor-metal piezotronic transistors are key piezotronic nanodevices for electromechanical applications, and they are typical nonlinear elements. In this paper, a simplified current-voltage analysis solution of piezotronic transistors is developed, which can be used for circuit design and simulation. Furthermore, the typical nonlinear circuit: Chua's circuit based on piezotronic transistors is simulated. We find that the output signal of the piezotronic transistor circuit can be switched and changed asymmetrically by externally applied strain. This study provides insight into the nonlinear properties of the piezotronic transistor, as well as guidance for piezotronic transistor nonlinear circuit application.

piezotronic transistor, nonlinear nanodevice, electromechanical application, nonlinear circuit

Citation: Hu G W, Zhang Y J, Luo L, et al. Piezotronic transistors in nonlinear circuit: Model and simulation. Sci China Tech Sci, 2015, 58: 1348–1354, doi: 10.1007/s11431-015-5873-5

1 Introduction

Piezoelectric semiconductors, such as wurtzite ZnO, GaN, and InN, have attracted increasing attention for their coupled piezoelectric and semiconductor properties [1]. Piezotronic effect is about the use of piezoelectric charges to tune/control the carrier transport characteristics at an interface or junction under applied strain, based on which, many unique electromechanical functional devices have been designed and developed, such as nanogenerators [2–4], piezoelectric field effect transistors [5], piezotronic sensors [6–8], logic devices [9], piezo-phototronic devices [10,11], piezotronic transistor and photonic-strain sensor array integrated system for flexible human-machine interface [12,13]. Recently, piezotronic transistors have been fabricated by two-dimensional (2D) single-atomic-layer MoS_2 [14]. As high sensitivity electromechanical functional electronic devices, piezotronic transistors can be used in force/pressure sensing, triggering, human-computer interfacing systems [15].

Theoretical studies have been demonstrated to understand carrier transport behavior for piezotronic transistors [16]. Based on this, a simulation model can be developed for circuit based on piezotronic transistors, and used for circuit design and application by electronic design automation (EDA) software systems. According to previous experimental and theoretical studies, piezotronic transistor has nonlinear current-voltage characteristics [6,16], which can

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*Corresponding authors (email: zhangyan@lzu.edu.cn; zlwang@gatech.edu) be turned or controlled by externally applied strain. Due to the novel tunable current-voltage characteristics, piezotronic transistor will play an important role in nonlinear circuit as a new kind of nonlinear element. For fundamental circuit element and nonlinear circuit, L. O. Chua and Yang [17,18] provided a series of systematic studies since 1971. One of the famous fundamental circuit element is memristor [17], which had not been found until HP Lab observed the memristance characteristics in the titanium dioxide cross-point nanoswitches with nonlinearities in ionic transport in 2008 [19]. Another famous example is Chua's circuit, which is the first nonlinear circuit to exhibit chaotic behavior [20]. Chaos theory plays a fundament role in nonlinear theory, since Ilya Prigogine developed the concept and theories of dissipative structures, complex systems and irreversibility, for which Ilya Prigogine won the 1977 Nobel Prize in Chemistry [21]. Chaos theory and method have been used for signal processing in automatic control circuit [22,23], secure communication [24–26], human healthy monitoring and diagnose, for example, brain and heart signal [27,28].

The Chua's circuit consists of two capacitors, an inductor, a linear resistor and a nonlinear resistor. In previous studies, the nonlinear resistor is made of equivalent circuit by linear resistors and operational amplifier [20]. However, the electromechanical nonlinear element for Chua's circuit has not been presented until now. Piezotronic transistors are distinctive candidates for both fundamental elements and nonlinear circuit.

In this paper, we present a theoretical study of piezotronic transistors for a typical nonlinear circuit. We first give some analysis for current-voltage characteristics of piezotronic transistors, which can be used for circuit design and simulation. Furthermore, we found that the states of the Chua's circuit based on piezotronic transistors can be switch by external applied strain. The theoretical results not only provide the principle for future design of piezotronic transistors based nonlinear circuit application, but also establish a theoretical platform for nonlinear theory of piezotronics.

2 Model of piezotronic transistor as nonlinear element

Typical piezotronic transistors are metal-semconductor-metal (MSM) structure nanodevices in previous experiments [12], as shown in Figure 1(a). Such a new property of piezotronic transistor can be applied by not only piezoelectric nanowires, but also nano-film and even bulk piezoelectric semiconductors. The equivalent circuit of MSM piezotronic transistors consists of two back to back metal-semiconductor contact diodes ($D1$ and $D2$) and a nanowire resistor (R) [29], as shown in Figure 1(b). Figure 1(c) shows the symbol of a piezotronic transistor, from the definition in ref. [12].

According to our previous studies [16], the current-voltage characteristics of metal-semiconductor contact diode with piezotronic effect can be given by

$$J = J_{D0}\exp\left(\frac{q^2\rho_{\text{piezo}}W_{\text{piezo}}^2}{2\varepsilon_s kT}\right)\left[\exp\left(\frac{qV}{kT}\right)-1\right], \qquad (1)$$

where J is the current density, q is the absolute value of unit electronic charge, $\rho_{\text{piezo}}(x)$ is density of polarization charges (in units of electron charge), W_{piezo} is a width of piezoelectric charges distribution at the interface of p-n junction, k is Boltzmann constant, T is absolute temperature, ε_S is the permittivity of the piezoelectric semiconductor material, V is applied voltage. J_{D0} is the saturation current density of MSM piezotronic transistor without external applied strain, which can be obtained from our previous work [16]:

$$J_{D0} = \frac{q^2 D_n N_C}{kT}\sqrt{\frac{2qN_D(\psi_{bi0}-V)}{\varepsilon_s}}\exp\left(-\frac{q\varphi_{Bn0}}{kT}\right), \qquad (2)$$

where J_{D0} is the saturation current density without external applied strain, D_n is diffusion coefficients for electrons, N_C is the effective density of states in the conduction band, N_D is the donor concentration, ψ_{bi0} and ϕ_{Bn0} are built-in poten-

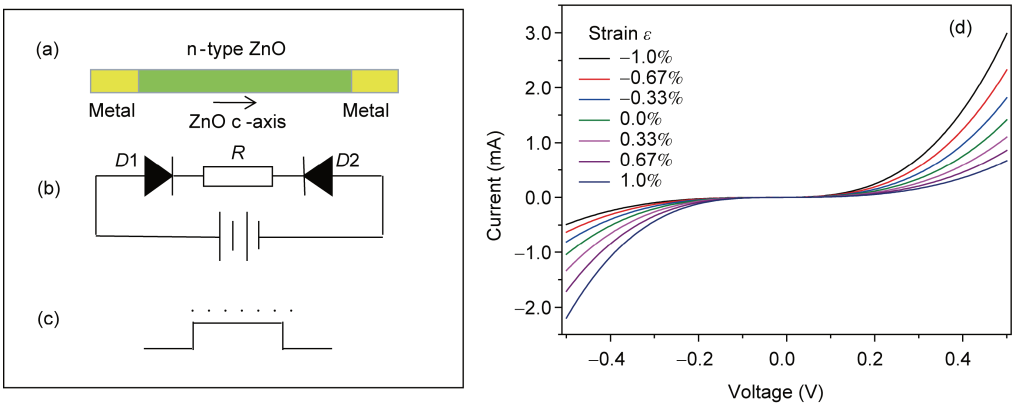

Figure 1 (a) Schematic of a metal-semiconductor-metal (MSM) piezotronic transistor; (b) Equivalent circuit of MSM piezotronic transistor; (c) the symbol of piezotronic transistor in circuit; (d) Current-voltage curves of piezotronic transistor model.

tial and Schottky barrier height with the absence of piezoelectric charges.

The current-voltage characteristics of a piezotronic transistor can be solved by Kirchhoff's laws in the equivalent circuit of an MSM piezotronic transistor as shown in Figure 1(b):

$$\begin{cases} I_{D1} = I_{D2} = I_{NW}, \\ V = V_{D1} + V_{D2} + V_{NW}, \\ I_{D1} = SJ_{D1}(V_{D1}), \\ I_{D2} = SJ_{D2}(V_{D2}), \\ I_{NW} = \dfrac{V_{NW}}{R}. \end{cases} \tag{3}$$

In general, there is no analysis solution for eq. (3), so numerical calculation or fitting method can be used for obtaining the current-voltage characteristics in our previous experiments and theoretical studies [29]. For piezotronic transistors based circuit design and application, the current-voltage characteristics are necessary in electronic design automation (EDA) software packages. For circuit design using by EDA, the circuit simulation model need include device structure and the current-voltage characteristics of piezotronic transistors. The current-voltage characteristics of piezotronic transistor is typical nonlinear and tunable under externally applied strain. The tunable characteristics are unique as nonlinear element. For simplicity, the resistor of nanowire can be ignored, while the Schottky barrier height is dominant in carrier transport of piezotronic transistor [29]. For cross-sectional area S of MSM piezotronic transistor, the approximate analysis solution of eq. (3) can be obtained by Taylor series:

$$\begin{aligned} I(V) \approx I_{D0} \exp\left(\frac{q^2 \rho_{\text{piezo}} {W_{\text{piezo}}}^2}{2\varepsilon_s kT}\right) \\ \times\left[\frac{1}{6}\left(\frac{qV}{kT}\right)^3 + \frac{1}{2}\left(\frac{qV}{kT}\right)^2 + \frac{qV}{kT}\right], \end{aligned} \tag{4}$$

where $I_{D0}=J_{D0}S$ is the saturation current without externally applied strain, which depends on materials and structures of the piezotronic transistor. For wurtzite ZnO piezotronic transistor with strain s_{33} along the c-axis, the current density can be obtained from eq. (3):

$$\begin{aligned} I(V) = I_{D0} \exp\left(\frac{q e_{33} s_{33} W_{\text{piezo}}}{2\varepsilon_s kT}\right) \\ \times\left[\frac{1}{6}\left(\frac{qV}{kT}\right)^3 + \frac{1}{2}\left(\frac{qV}{kT}\right)^2 + \frac{qV}{kT}\right]. \end{aligned} \tag{5}$$

The current-voltage characteristics of piezotronic transistor under various strain is shown in Figure 1(d). According to our previous works [16], the device and material parameters of wurtzite ZnO is: piezoelectric constant e_{33} = 1.22 C/m^2, relative dielectric constant 8.91, the width of the piezo-charges W_{piezo} = 0.25 nm, and The temperature T is 300 K.

Figure 1(d) shows I as a function of the externally applied voltage V and strain. I increases with the external voltage increase, at the strain changes from −1% to 1%. The current-voltage curves show asymmetrical change in the positive and negative voltage range, as shown in Figure 1(d). When a positive voltage is applied to the piezotronic transistor in Figure 1(b), the current-voltage characteristics is dominated by the reversely biased contact at the right-hand side because contact at the left-hand is under forward bias. Under negative strain (compressive strain), negative piezoelectric charges at the right-hand contact raise the Schottky barrier height (SBH), thus lower the current comparing to the piezotronic transistor without externally applied strain. For positive strain (tensile strain) case, positive piezoelectric charges at the right-hand contact lower the SBH and thus raise the current in the piezotronic transistor. Alternatively, at the negative voltage case, the current-voltage characteristics depend on the contact at the left-hand side because the contact at the right-hand side is at positive bias. The current-voltage curves show opposite trend under the same strain. Therefore, piezotronic transistor has unique current-voltage property of the asymmetry: (1) Piezotronic transistor is a nonlinear element; (2) piezotronic transistor has polarity under external applied strain; (3) the polarity is tunable under externally applied strain, which mean the polarity of piezotronic transistor can reverse while the sign of external applied strain changes. The unique tunable property of asymmetry of piezotronic transistor will provide new function in nonlinear circuit. The piezoelectric charges can be act as key factor for charactering the asymmetry, both in sign and magnitude. The simplified model can be not only used for circuit design EDA software, such as Mutilsim, Pspice, Matlab, etc., but also interesting in theoretical study, for example, nonlinear dynamic.

3 Nonlinear circuit base on piezotronic transistor

Chua's circuit is a simple nonlinear circuit that can exhibit complex behavior [20]. Figure 2 shows the schematic circuit diagram of Chua's circuit based on piezotronic transistors, and it includes an inductor (L), two capacitors (C_1 and C_2), a resistor (R) and a nonlinear resistor made by piezotronic transistor (R_N). From circuit element point of view, capacitors, inductor, and resistor are linear elements. The capacitors and inductor store energy, but the resistor consumes energy. The nonlinear element has function of frequency conversion, which will play the role of producing different frequency signals. The piezotronic transistor can be used as tunable nonlinear element in circuit applications.

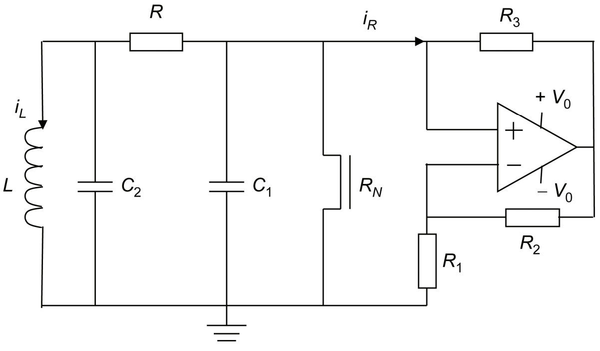

Figure 2 Schematic of Chua's circuit based on piezotronic transistor.

3.1 Output signal of nonlinear circuit based on piezotronic transistor without applied strain

For circuit design and simulation in EDA, the dynamical behavior of circuit is described by ordinary differential equations. Here, Chua's circuit is given by

$$\begin{cases} \dfrac{\mathrm{d}v_{c1}}{\mathrm{d}t} = \dfrac{G}{C_1}(v_{c2}-v_{c1}) - \dfrac{1}{C_1}I(v_{c1}), \\ \dfrac{\mathrm{d}v_{c2}}{\mathrm{d}t} = \dfrac{G}{C_2}(v_{c1}-v_{c2}) - \dfrac{i_L}{C_2}, \\ \dfrac{\mathrm{d}i_L}{\mathrm{d}t} = -\dfrac{1}{L}v_{c2}, \end{cases} \tag{6}$$

where v_{c1} and v_{c2} are the voltage of C_1 and C_2, $G=1/R$, i_L is the current of L and $I(v)$ is eq. (5), which is a nonlinear function described the current-voltage characteristics of piezotronic transistor. For the case of strain-free, the piezotronic transistor acts as a nonlinear element. While the circuit element parameters are chosen as following: the resistor is R=2.86 kΩ, L=8.2 mH, c_1=0.005 uF and c_2=0.05 uF, the output of Chua's circuit is a periodic signal. Figure 3(a) shows output signal (the voltage of C_1) as a function of time, and it is a periodic output. The Chua's circuit based on piezotronic transistor can be as oscillator in this work. The

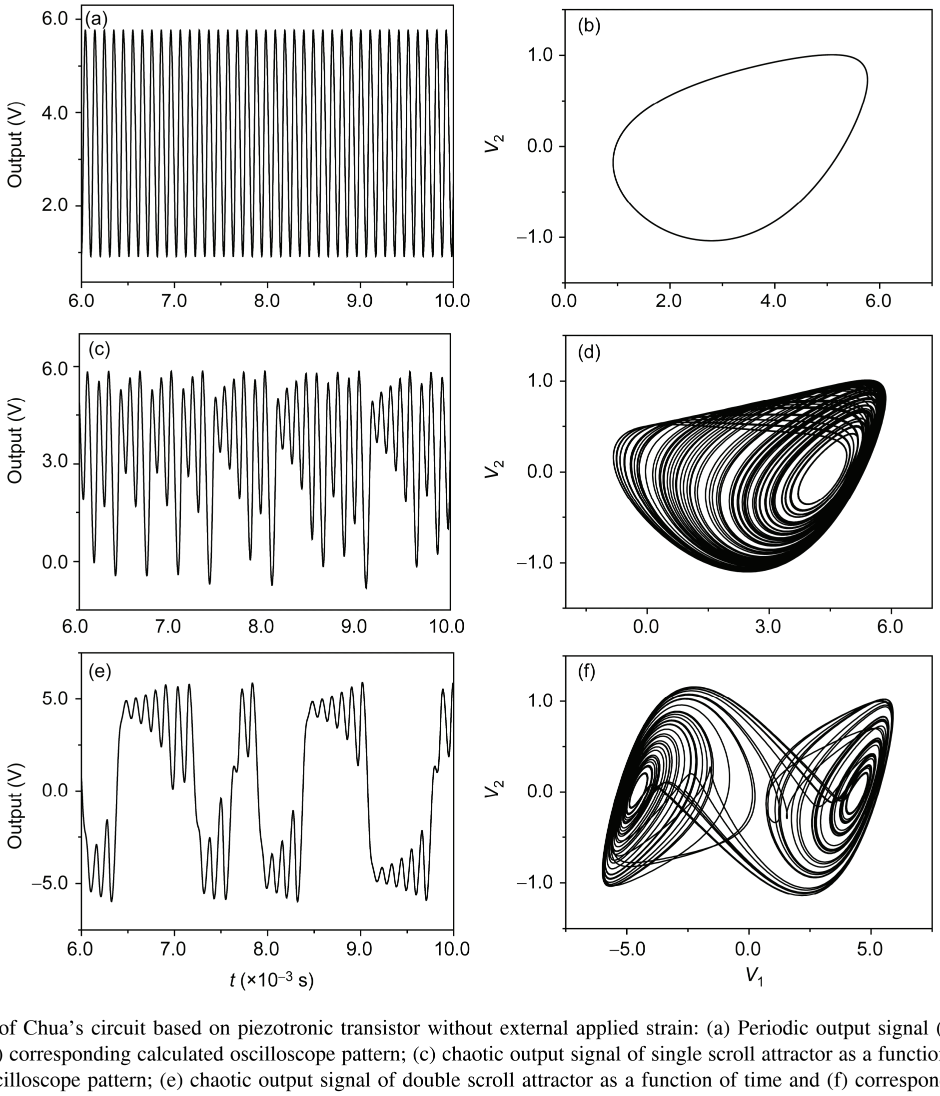

Figure 3 The output of Chua's circuit based on piezotronic transistor without external applied strain: (a) Periodic output signal (the voltage of C_1) as a function of time and (b) corresponding calculated oscilloscope pattern; (c) chaotic output signal of single scroll attractor as a function of time and (d) corresponding calculated oscilloscope pattern; (e) chaotic output signal of double scroll attractor as a function of time and (f) corresponding calculated oscilloscope pattern.

period signal output of piezotronic transistor nonlinear circuit depends on inductor and capacitors, which are important parameters for signal generator at nanoscale. It is predictable that the values of circuit element parameters will reduce due to the small size of nanoelements and nanostructured piezotronic transistors. It will provide high frequency signal output. Figure 3(b) shows the calculated oscilloscope pattern of output signal: the voltage of C_1 and C_2, which can be observed in experiments by using a oscilloscope configured in X-Y mode. For R=2.68 kΩ, the output will exhibit chaotic signal with single output voltage change regime, which be called as single scroll attractor according to nonlinear theory [30]. The output signal shows as a function of time in Figure 3(c), corresponding oscilloscope pattern is shown in Figure 3(d). Although the chaotic signal looks like a random signal from Figure 3(c), there are complex and ordered behaviors from nonlinear theoretical point of view [31]. For chaotic signal, Lyapunov exponent (LE) provides a quantitative criterion for characterization of the circuit states [31]. When the output signal of Chua's circuit (v_{c1} or v_{c2}) is chaotic signal, LE > 0. The output signal is nonchaotic while Lyapunov exponent is less than or equal to zero. In this case, we calculated LE = 0.29. For R=2.56 kΩ, two different output voltage change regime oscillation is shown in Figure 3(e), which is called as double scroll attractor. The corresponding oscilloscope pattern obviously shows two different change regimes, as shown in Figure 3(f). The calculated LE is 0.30 in this case.

3.2 Nonlinear circuit states switch by piezotronic transistor under applied strain

Piezotronic transistor can be tunable by externally applied strain. The current-voltage characteristics will change under various strains. Thus, the circuit work states are controlled by strain. Figure 4(a) shows the strain applied on the piezotronic transistor as a function of time, and the switch strain changes the circuit output:

Period signal—At R=2.86 kΩ, the circuit will output period signal. When the strain switches from 1.0% to –1.0%, Figure 4(b) shows the amplitude regime of a period signal from (–1.5 to –8.5 V) to (1.5 to 8.5 V).

Chaotic signal—At R=2.68 kΩ, the circuit will output chaotic signal of a single scroll attractor. When the strain switches from 1.0% to –1.0%, Figure 4(c) shows the amplitude regime change from (1.6 to –8.5 V) to (–1.6 to 8.5 V). While at R=2.56 kΩ, the circuit will output chaotic signal of double scroll attractor. When the strain switches from 1.0% to –1.0%, Figure 4(d) shows the amplitude regime change from (4.0 to –8.5 V) to (–4.0 to 8.5 V). For chaotic signal, the work states switch for output voltage is not obviously different in Figures 4(c) and (d), because the signal has complex properties. For signal analysis, the corresponding oscilloscope pattern will distinguish the output voltage states clearly, which can be verified in experiment using a oscilloscope.

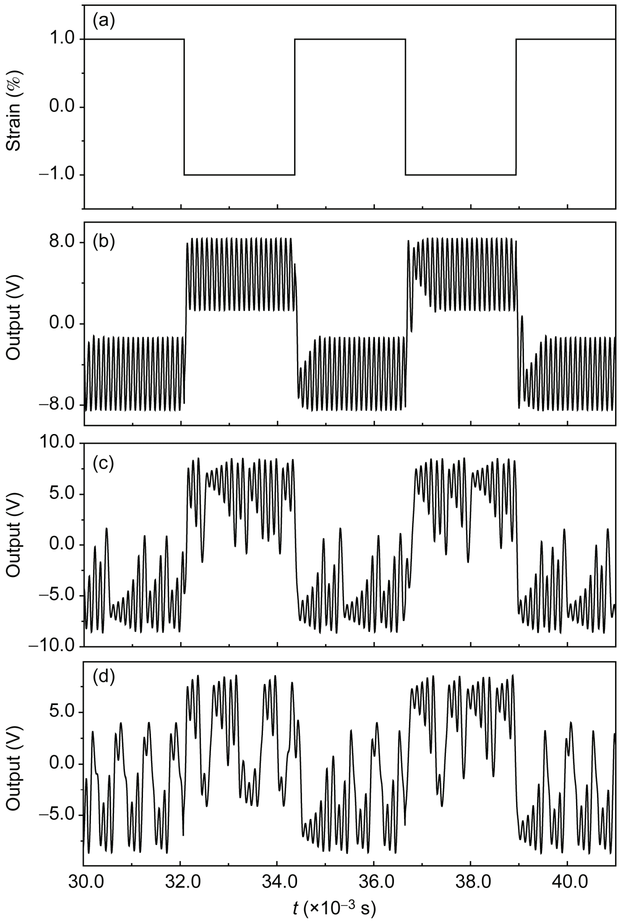

Figure 4 (a) The applied strain switch from 1.0% to −1.0%, and the output of Chua's circuit based on piezotronic transistor switch by external applied strain; (b) periodic signal, (c) chaotic output signal of single scroll attractor, and (d) chaotic output signal of double scroll attractor.

Figures 5(a) and (b) show the oscilloscope pattern of period at 1.0%, 0, −1.0% strain. The period signal change asymmetrically. The oscilloscope pattern of a single scroll attractor chaotic signal at 1.0%, −1.0% strain is shown in Figures 5(c) and (d), respectively. There is obviously asymmetry of oscilloscope pattern between 1.0% and −1.0% strain, indicating the output property of circuit change, in other words, the circuit change work states. For chaotic signal of double scroll attractor, the oscilloscope pattern show obviously asymmetry, as shown in Figures 5 (e) and (f), respectively. Furthermore, the amplitude regime of left-hand scroll is larger than that at the right-hand scroll at 1.0% strain in Figure 5(e). In this positive strain case, the current of piezotronic transistor at positive bias is larger than the reversely biased current, thus the output voltage of the circuit at the left-hand scroll states is large than that at the right-hand scroll. As a result, the oscilloscope pattern shows that the change range of output voltage is different, as well as size of scroll. Alternatively, negative strain makes

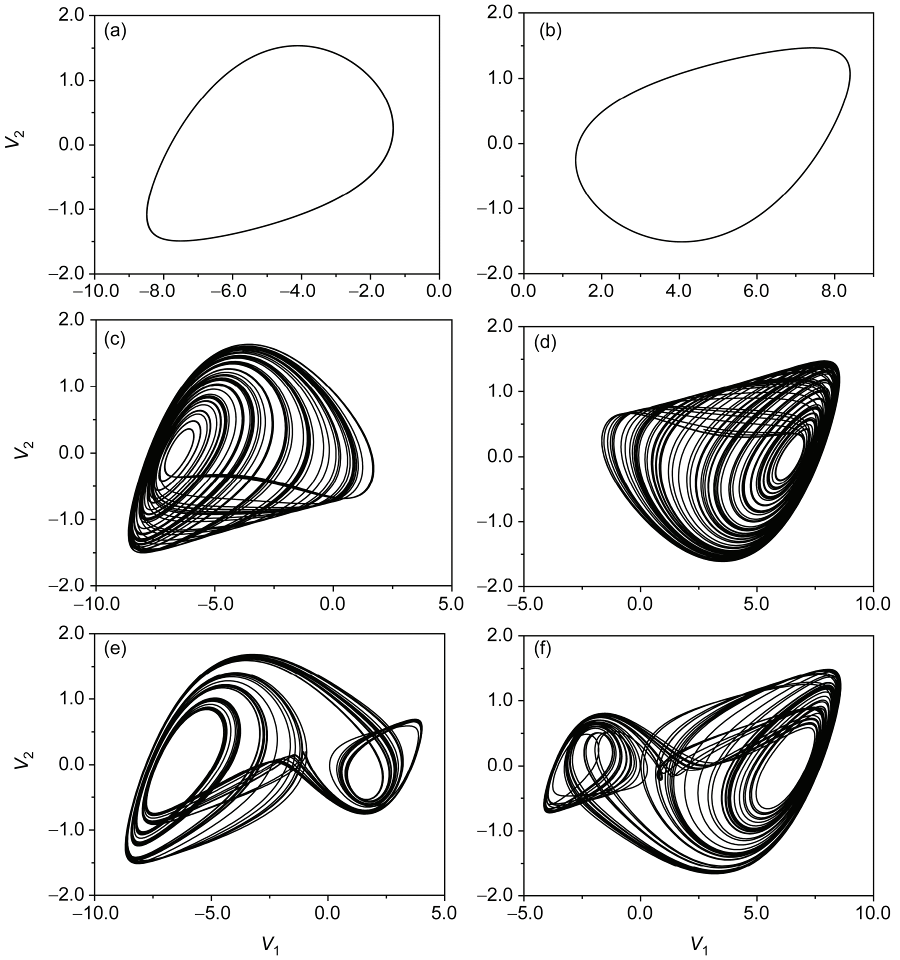

Figure 5 The calculated oscilloscope pattern of output signal under external applied strain: Periodic output signal (a) at 1.0% strain and (b) at −1.0% strain; chaotic output signal of single scroll attractor (c) at 1.0% strain and (d) at −1.0% strain; chaotic output signal of double scroll attractor (e) at 1.0% strain and (f) at −1.0% strain.

the right-hand part larger than that at the left-hand side at 1.0% strain in Figure 5(f). Comparing to strain-free case in Figure 3(f), the current of piezotronic transistor at positive bias is similar to the reversely biased current. Thus, the amplitude regimes of the left-hand and right-hand scroll are of the same level, so that the oscilloscope pattern shows symmetrical scroll. Above dynamical behaviors is unique in Chua's circuit based on piezotronic transistor, indicating piezotronic device can play important role in nonlinear circuit application.

For circuit application, piezotronic transistor can be used as nonlinear element, which can be found in many kinds of nanodevices [32]. In this mode, the circuit based on piezotronic transistor can be used for oscillator application system to output period and chaotic signal. Furthermore, piezotronic transistor has tunable polarity under external applied strain. These unique electromechanical functions can be used for nonlinear circuit states tuned/controlled by external applied strain. For low cost and low power nanosystems, multi-function with few elements is very important. Therefore, electromechanical function nonlinear circuit based on piezotronic transistor can be applied in circuit control and smart sensor system at nanoscale.

In summary, we have presented the theoretical model of current-voltage characteristics of piezotronic transistors as a non-linear element. The output of Chua's circuit based on piezotronic transistors is simulated. The tunable piezotronic transistors can switch the circuit work states, such as amplitude of output signal for both period and complex signal output. Possible experiment design and application can be constructed by ZnO nanowire or GaN film piezotronic transistor. It should be pointed that in application at nanoscale, the GaN piezotronic transistor is a typical realization by modern semiconductor technology. Furthermore, the piezotronic transistors can tune the circuit states asymmetrically for chaos signal output. The study presented here provides the first theoretical model for piezotronic transistor in nonlinear circuit design.

This work was supported by the Natural Science Foundation of Gansu Province, China (Grant No. 145RJZA226), Fundamental Research Funds for the Central Universities (Grant No. lzujbky-2013-35), and Beijing

Municipal Commission of Science and Technology (Grant Nos. Z131100006013005 and Z131100006013004).

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