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MAKING CHUA'S DIODE WITH A SCHOTTKY DIODE-BRIDGE-FED JFET MOSFET

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Highlights

- A Chua's Diode With A Schottky Diode-Bridge-Fed JFET Mosfet.
- Calculation of the PWL parameters of the Chua's diode.
- The verification of the chaotic behavior of the Chua's circuit with simulations and experiments.

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Abstract

The nonlinear element of a Chua circuit is called Chua's diode. It is important to make a Chua's diode with cheap and easy-to-find components. In this study, a circuit that consists of an n-type JFET fed by a Schottky diode bridge and a resistor is used to make a Chua's diode. Such components are inexpensive off-the shelves components. 1N5819 Schottky diodes and an n-type JFET BF245B are used in this study. Piecewise-linear Chua's diode parameters are calculated using the circuit elements. The Chua's circuit with the suggested Chua's diode is simulated with Simulink to see whether it shows chaotic behavior or not. After the verification of its chaotic behavior with simulations, experiments are also performed to show the circuit's chaotic behavior. The experimental results deviate from the simulation results. The reason has been diagnosed as the tolerances of the circuit parameters.

SCHOTTKY KÖPRÜ DİYOT İLE BESLENEN JFET TİPİ MOSFET KULLANILARAK YAPILAN CHUA DEVRESİ

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kaotik osilatörler;
kaos;
JFET

Öz

Chua devresinde kullanılan doğrusal olmayan devre elemanına Chua diyodu denir. Chua diyotunun kolay bulunabilir ve ucuz devre elemanları ile yapılması önemlidir. Bu çalışmada, bir Chua diyotu yapmak için bir Schottky diyot köprüsünden beslenen n-tipi JFET ve bir dirençten oluşan bir devre kullanılmış ve bununla bir Chua devresi yapılmıştır. Bu devre elemanları hem ucuzdur, hem de kolayca bulunabilirler. 1N5819 Schottky diyotlar ve bir n-kanallı JFET olan BF245B devrenin yapımında kullanılmıştır. Parçalı doğrusal Chua diyodunun parametreleri, devre elemanlarının parametreleri kulla nılarak hesaplanmıştır. Önerilen Chua diyotlu Chua devresinin kaotik davranış gösterip göstermediğini görmek için Simulink ile simüle edilmiştir. Kaotik davranışın simülasyonlarla doğrulanmasının ardından, devrenin kaotik davranışını göstermek için deneyler de yapılmıştır. Deneysel sonuçlar simülasyon sonuçlarından sapmaktadır. Bunun sebebinin devre parametrelerinin toleransları olduğu anlaşılmıştır.

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1. Introduction

Chaos has been discovered in 1963 (Lorenz 1963, Lorenz 1963). The output of deterministic chaotic systems is quite dependent on its initial conditions (Lorenz 1972). The first circuit, which shows such a chaotic behavior, is called the Chua circuit after its inventor. It is pretty famous and commonly used in chaotic studies (Matsumoto 1984, Madan 1993, Chua 1992, Haken 1975, Knobloch 1981, Hemati 1994). The Chua circuit employs a nonlinear circuit element called the Chua's diode (Chua 1999, Recai 2010, Chua 2007). The Chua's diode must be locally active (Chua 2005). There are various types of Chua's diodes in literature (Zhong 1994, O'Donoghue et.al, 2005, Muthuswamy 2010, Yener et.al 2014, Kennedy 1992, Yesil 2019, Arena et.al. 1995, Khibnik et.al 1993). Different Chua's diodes result in different chaotic dynamics (Zhong 1994, O'Donoghue et.al, 2005, Muthuswamy 2010, Yener et.al 2014, Kennedy 1992, Yesil 2019, Arena et.al. 1995, Khibnik et.al 1993, Dana et.al. 2005, Yamaçlı et.al. 2011). Some of Chua's diodes employ ordinary diodes and negative resistor circuits to obtain a piece-vice linear characteristic (Matsumoto 1984, Madan 1993, Chua 1999, Recai 2010, Chua 2007, Chua 2005, Zhong 1994, O'Donoghue et.al, 2005, Muthuswamy 2010, Yener et.al 2014, Kennedy 1992, Yesil 2019, Arena et.al. 1995, Khibnik et.al 1993, Dana et.al. 2005, Yamaçlı et.al. 2011, Chua et.al. 1983, Sedra et.al. 1998, Xu et.al. 2015). The voltage-current characteristic of a JFET Mosfet for a constant bias is well-known (Sedra 1998). In our opinion, the characteristic is pretty similar to the piecewise linear (PWL) Chua's diode characteristic (Matsumoto 1984, Chua 1992, Arena et.al. 1995) and it can be used to make a Chua's diode by combining it with a negative resistor circuit. Here, in this study, it is suggested that a JFET type Mosfet can be used to replace one of the resistors in the negative resistor circuit to make a Chua's diode and, therefore, a Chua's circuit is made with it. The suggested Chua's diode is made with off-the shelves and cheap elements such as a JFET type Mosfet and Schottky diodes. The JFET parameters and other circuit element parameters are used to calculate the desired Chua's circuit equation parameters. The circuit behavior is examined using simulations in Simulink™ toolbox of Matlab™.

The remainder of this paper is organized as follows. The Chua's circuit, the Chua's diode, and its PWL function are briefly told in the second section. A Chua's diode based on an n type JFET, a resistor, and a Schottky diode bridge is introduced in the third section. Its simulations are given in the fourth section. Its experimental results are given in the fifth section. The conclusions are given in the final section.

2. The Chua Circuit, The Chua's Diode, And Its Piecewise-Linear (Pwl) Function

There are different types of Chua's diodes (Matsumoto 1984, Madan et.al. 1993, Chua 1999, Yamaçlı et.al. 2011, Chua 1983). The Chua's circuit is shown in Figure 1. It consists of two capacitors, an inductor, a resistor, and a nonlinear circuit element called Chua's diode. The state-equations for the Chua's circuit is given as follows:

$$
\begin{aligned}
C_1 \frac{dv_{c_1}(t)}{dt} &= G\left(v_{c_2}(t) - v_{c_1}(t)\right) - g(v_{c_1}(t)) \\
C_2 \frac{dv_{c_2}(t)}{dt} &= G\left(v_{c_1}(t) - v_{c_2}(t)\right) + i_L(t) \qquad (1) \\
L \frac{di_L(t)}{dt} &= -v_{c_2}(t)
\end{aligned}
$$

where $v_{c_1}(t)$, $v_{c_2}(t)$, and $i_L(t)$ are the circuit state variables, t is time. C_1, C_2, L, and $G = \frac{1}{R}$ are the parameters of the circuit elements.

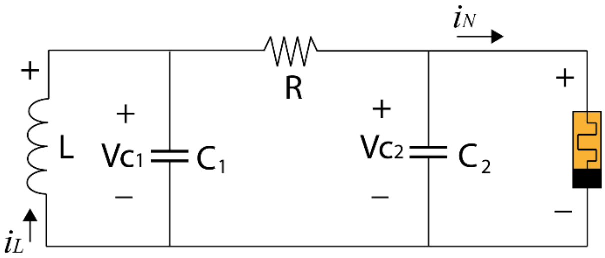


Figure 1. The Chua circuit (Matsumoto 1984).

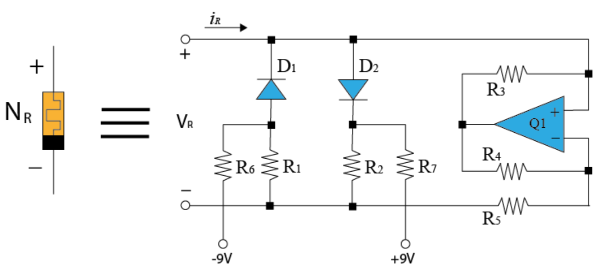
The Chua's diode is made using a negative resistor (N_R) circuit and nonlinear circuit elements such as diodes (Matsumoto 1984, Madan 1993, Chua 1999, Recai 2010, Chua 2007, Khibnik 1993, Yamaçlı 2011, Chua 1983). Three different Chua's diode topologies are given as examples shown in Figure 2. A piecewise-linear (PWL) Chua's diode characteristic is commonly used in Chua's circuit (Matsumoto 1984, Madan 1993, Chua 1999, Recai 2010, Chua 2007, Khibnik 1993, Yamaçlı 2011, Chua 1983). and the characteristic used in (Kennedy 1992) is shown in Figure 3. $g(v_{neg})$ is the piecewise-linear function of the Chua's diode (Kennedy 1992) and it is defined by:

$$g(v_{neg}) = m_0 v_{neg} + \frac{m_1 - m_0}{2}\left(\left|v_{neg} + B_P\right| - \left|v_{neg} - B_P\right|\right) \qquad (2)$$

where V_{neg} is the Chua's diode voltage and B_P is the breaking point voltage, m_0 and m_1 are the slopes shown in Figure 3.

The Chua's diode current is given as

$$I_{neg} = g(v_{neg}) = m_0 v_{neg} + \frac{m_1 - m_0}{2}\left(\left|v_{neg} + B_P\right| - \left|v_{neg} - B_P\right|\right) \qquad (3)$$



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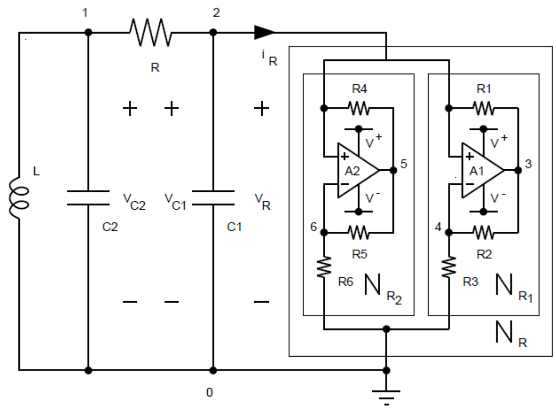

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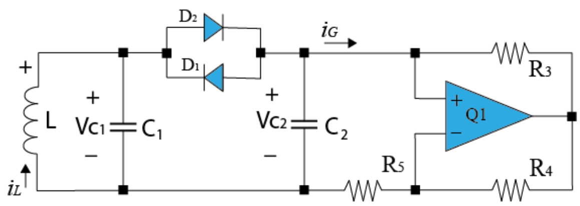


(c)

Figure 2. Three examples of the Chua's diodes taken from **a)** (Matsumoto 1984), **b)** (Kennedy 1992), and **c)** (Xu 2015).

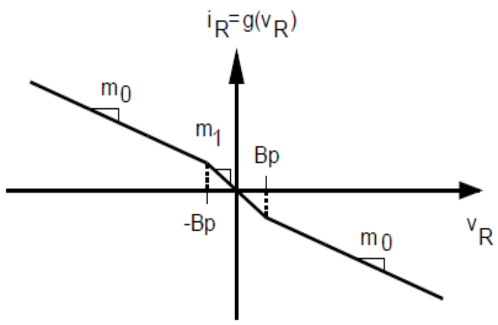


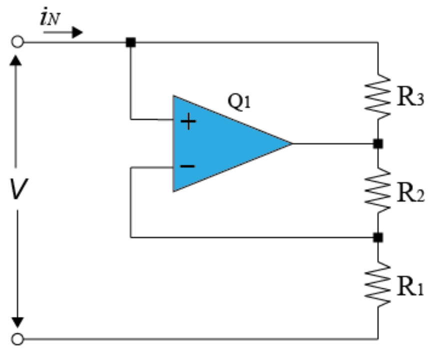
Figure 3. Three-segment piecewise-linear (PWL) ***v-i*** characteristic of the Chua's Circuit (Kennedy 1992).

m_0 and m_1 parameters given in Eq. (3), which are the tangents of the PWL characteristic, are shown in Figure 3. Eq. (3) can also be written as the PWL function:

$$g(V_{neg}) = \begin{cases} m_1 V_{neg} + m_1 - m_0 & ,if \quad V_{neg} \le BP \\ m_0 V_{neg} & ,if \quad -BP \le V_{neg} \le BP \\ m_1 V_{neg} + m_1 - m_0 & ,if \quad -BP \le V_{neg} \end{cases} \qquad (4)$$

3. A Chua's Diode Made with A Schottky Diode Bridge-Fed Jfet

An opamp-based negative resistor circuit is shown in Figure 4.a. The nonlinear circuit part of the Chua's diode, which consists of a Schottky diode bridge feeding an n-type JFET connected in parallel with an LTI resistor R_p, used in this study is shown in Figure 4.b. R_1 of the negative resistor is replaced with the nonlinear circuit to obtain a new type of Chua's diode as shown in Figure 4.c. Chua's circuit with this component is shown in Figure 4.d. Usage of the Schottky diodes is preferred due to their low threshold voltage, which is around 0.2-0.3 volt. The Schottky diode bridge is used to obtain the odd voltage-current characteristic shown in Figure 3, i.e. the voltage-current characteristic appears at the input of the Schottky diode bridge when excited with a low frequency signal.



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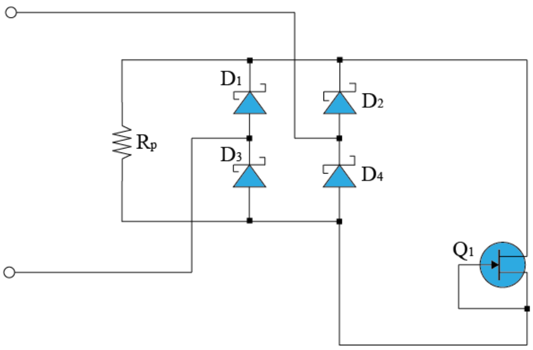

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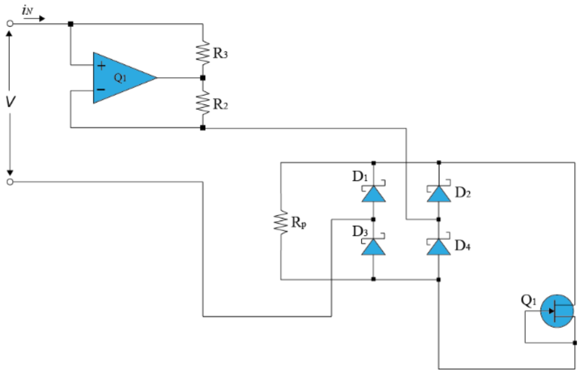

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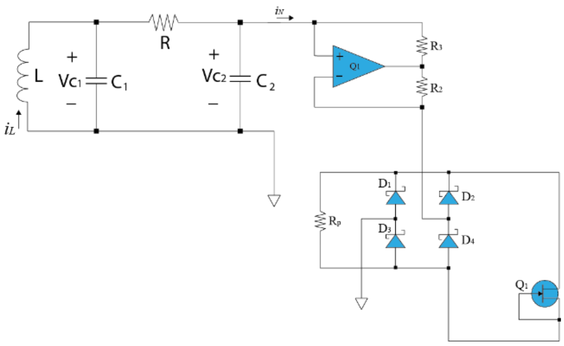


(d)

Figure 4. a) The opamp-based negative resistor circuit, **b)** The nonlinear circuit to replace R1,
c) The modified negative resistor circuit or the new Chua's diode studied in this paper,
d) The modified Chua's circuit with the Chua's diode studied in this paper.

4. Calculation of The Desired Parameters of the New Chua's Diode

The formulas necessary to calculate the desired parameters of the new Chua's diode, using m_o and m_1, are given in this section. The PWL Chua's diode characteristic and its slopes m_o and m_1 are shown in Figure 3. Considering both Figure 3 and Figure 5, the circuit parameters needed to obtain chaos can be calculated as follows.

Considering the JFET current equation:

$$I_D = K\left(\left(V_{GS} - V_T\right)V_{DS} - \left(V_{DS}\right)^2 / 2\right) \tag{5}$$

The JFET saturation current is

$$I_{sat} = G_{sat}V_{sat} = G_{sat}V_{DSsat} \tag{6}$$

where I_{sat} is the saturation current, G_{sat} is the saturated conductance of the JFET for $V_{GS}=0$ Volt and $V_{DS}=V_{GS}-V_T$, and $V_{DSsat}=V_{GS}-V_T$.

The following must be true:

$$V_{DSsat}=B_p \tag{7}$$

Using the saturated conductance of the JFET and its parallel resistor value, the following tangent parameters can be obtained as

$$m_0=-1/R_p \tag{8}$$

and

$$m_1=-G_{sat}-1/R_p, \tag{9}$$

respectively. R_p is the resistance of the resistor which is connected in parallel to the JFET to have a slope other than zero in the saturation region of the JFET.

Then, the negative resistor resistance can be found as

$$R_{neg}=-R_3R_{AB}/R_2 \tag{10}$$

The negative resistor current is calculated as

$$I_{neg}=-R_2V_{neg}/(R_3R_{AB}) \tag{11}$$

where R_{AB} is the input resistance of the diode bridge shown in Figure 4.c.

If $R_2=R_3$ is chosen, the Chua's diode current becomes equal to the negative of the diode bridge input current:

$$I_{neg}=g(v_{neg})=m_0v_{neg}+\frac{m_1-m_0}{2}\left(|v_{neg}+B_P|-|v_{neg}-B_P|\right)=-V_{neg}/R_{AB} \tag{12}$$

5. Selection of Components of the New Chua's Diode

Table 1. Parameters of the Circuit Components (Kennedy 1992).

R	1400 Ohm
C_1	5.56e-9 Farad
C_2	50e-9 Farad
L	7.14e-3 Henry
R_P	2000 Ohm

The scaling of Chua's circuit is explained in (Kennedy 1992). The Chua's circuit parameters and the PWL characteristic parameters taken from (Kennedy 1992) given in Tables 1 and 2 respectively are used in this study.

Table 2. Chua's diode's scaling values (Kennedy 1992).

m_0	-0.5e-3 S
m_1	-0.8e-3 S
B_P	6 Volt

The PWL characteristic of the Chua diode taken from (Kennedy 1992) is shown in Figure 5.

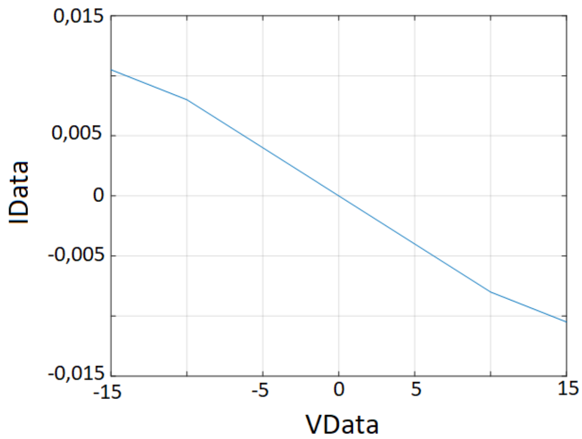


Figure 5. The PWL characteristic reproduced from (Kennedy 1992).

An n-type JFET BF245B is chosen for the Chua's circuit due to its low current specification and its availability. Its characteristic is shown in Figure 6. The breaking point voltage BP is around 2.2 Volt for the characteristic shown in Figure 6. The 1N5819 Schottky diode is chosen for the full-wave rectifier bridge and its characteristic is shown in Figure 7. The equivalent characteristic of the JFET and the resistor R_p connected in parallel is shown in Figure 8. Using the 1N5819 Schottky diode bridge, the even function characteristic given in Figure 9 is obtained. However, even though, Schottky diode threshold is low, it still does exist and produces a dead zone as seen in Figure 9. 1N5819 Schottky voltage drop produces a dead zone in their equivalent characteristic since they are used together. Not to change the characteristic of the Chua diode with the voltage applied across the gate and source nodes, We let $V_{GS}=0$ Volt. When $V_{DS} \geq V_{GS} - V_T$ or the BF245B JFET is under saturation region, the n-type JFET current becomes almost constant as shown in Figure 6. It has some slope but it is not enough to obtain chaotic behavior. However, due to the PWL characteristic of the Chua's diode, a higher slope (m_0) is needed. It can be obtained by placing a resistor (R_p) in parallel with the n-type JFET as shown in Figure 4. The conductance of the resistor should be chosen less than the JFET's in the linear and knee region. Its value is calculated as

$$R_p=-1/m_0=1/0.5e\text{-}3=2000 \text{ Ohm} \quad (13)$$

The voltage-current characteristic seen from inputs of 1N5819 Schottky diode bridge with 0.2 Volt threshold voltage feeding the BF245B JFET for V_{GS}=0 Volt is shown in Figure 9. The current-voltage characteristic of the negative resistor circuit given in Figure 4 is shown in Figure 10. A power opamp Opa544, which is usually used as an audio amplifier, is chosen so that it could supply the currents required with the circuit components.

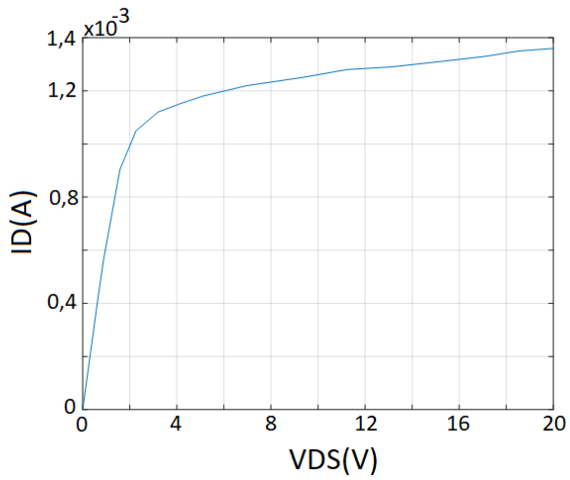


Figure 6. V_{DS}-I_D characteristic of BF245B JFET obtained experimentally.

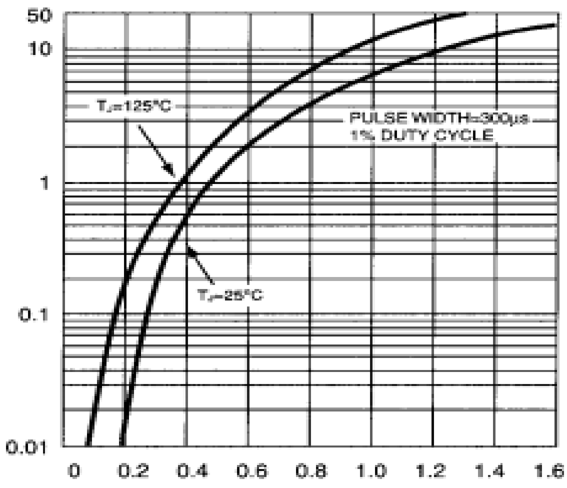


Figure 7. 1N5819 Schottky diode characteristic (Alldatasheet (15.05.2021))

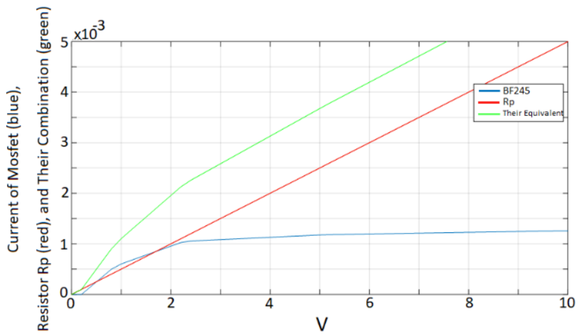


Figure 8. a) Resistor R_p characteristic shown in red, **b)** The BF245B JFET characteristic for V_{GS}=0 Volt shown in blue, and **c)** Their combined characteristic shown in green.

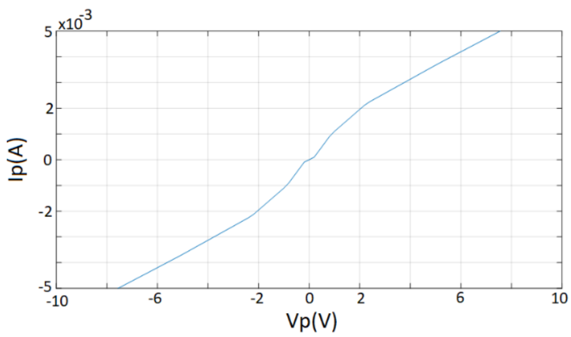


Figure 9. The voltage-current characteristic of R_P connected in parallel with 1N5819 Schottky diode bridge feeding the BF245B JFET for V_{GS}=0 Volt.

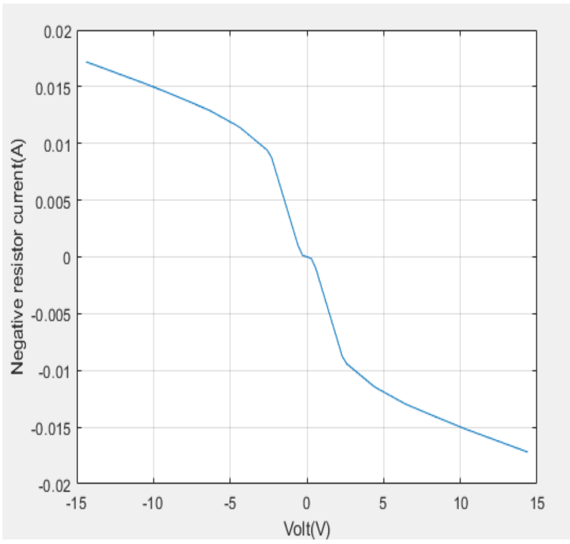


Figure 10. The current-voltage characteristic of the negative resistor circuit given in Figure 4.

6. Simulations

The Chua circuit is simulated in Simulink toolbox of MATLAB. Its block diagram is shown in Figure 11. Its time-domain waveforms are shown in Figure 12. Its phase portraits are given in Figure 13. The simulated waveforms in Figures 12 and 13 demonstrate chaotic behavior and strange attractors. Since the strange attractors in Figures 12 and 13 are chaotic, they exhibit sensitive dependence on initial conditions. Therefore, any two arbitrarily near alternative initial points on an attractor, after various numbers of iterations, lead to points that are arbitrarily far apart subjecting to the limits of the attractor.

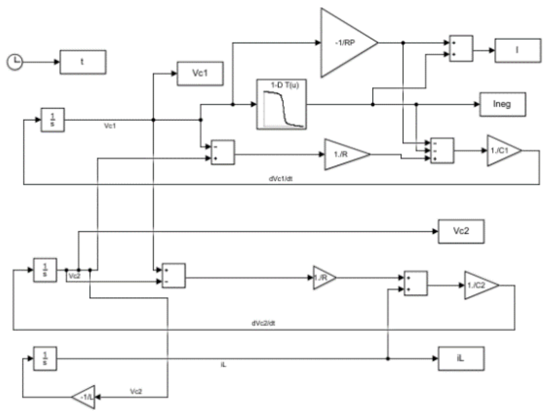
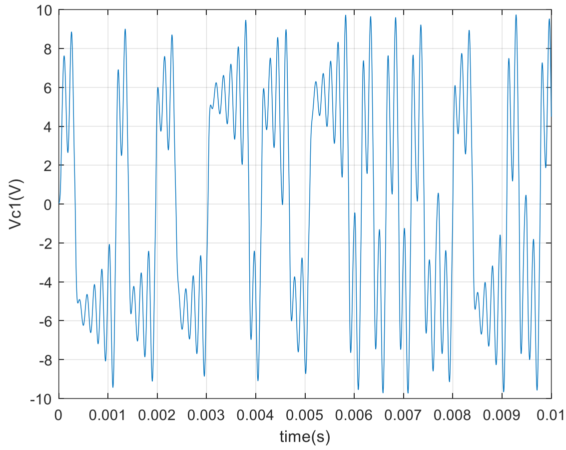


Figure 11. The Simulink block diagram of the system.



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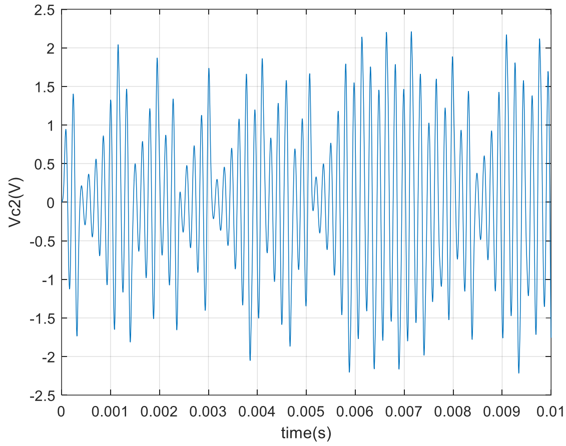

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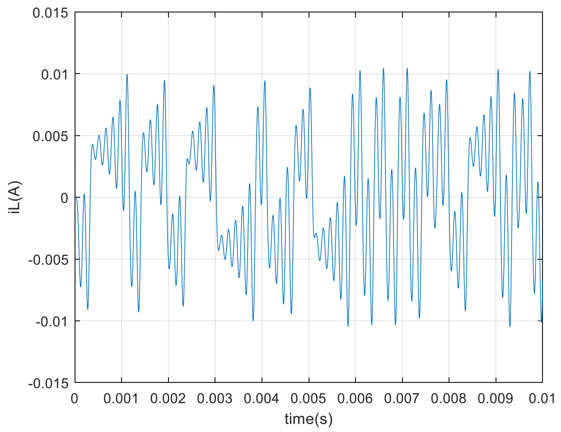


(c)

Figure 12. The circuit waveforms:
a) V_{c1} vs. t, **b)** V_{c2} vs. t, and **c)** i_L vs. t.

Those points, after various other numbers of iterations, lead to points that are arbitrarily near together. As shown in Figures 12 and 13, the simulated circuit with the chaotic attractors is globally stable yet locally unstable. This means that once some sequences have entered any of the attractors, nearby points deviate from one another but never go away from the attractor. The phase portrait of the circuit is also plotted in three dimensions as shown in Figure 14. The suggested Chua's diode and the Chua circuit made with it perform well as shown with the simulations due to the existence of the strange attractors.

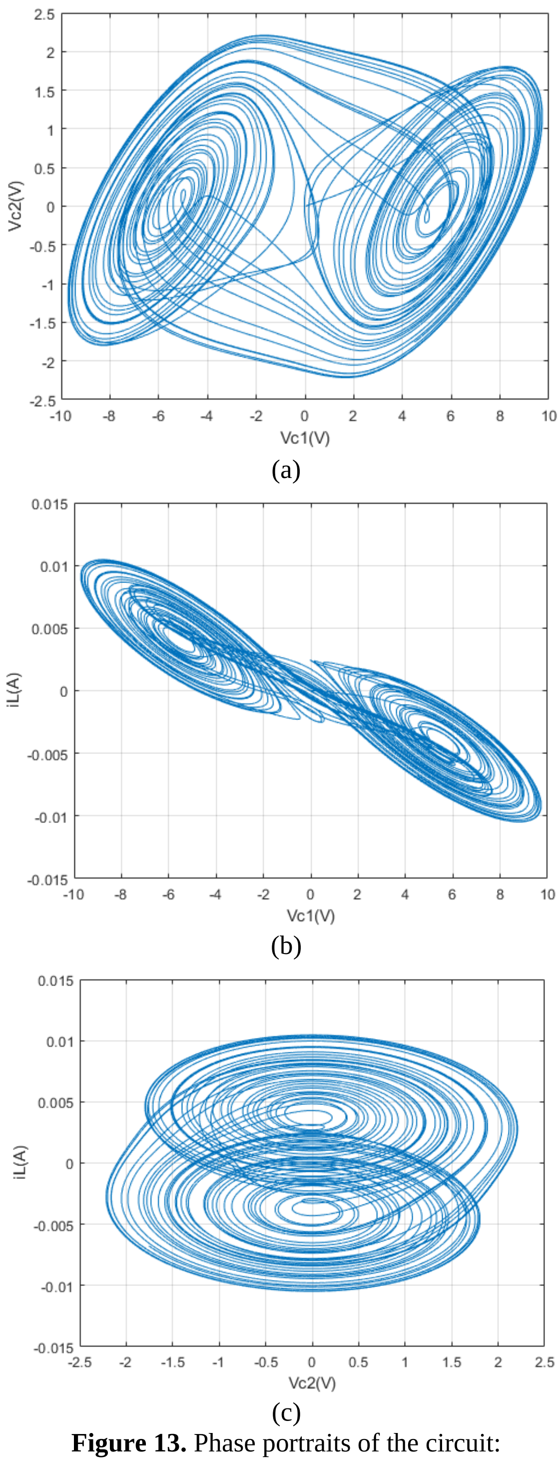


Figure 13. Phase portraits of the circuit:
a) V_{c2} vs. V_{c1}, **b)** i_L vs. V_{c1}, and **c)** i_L vs. V_{c2}.

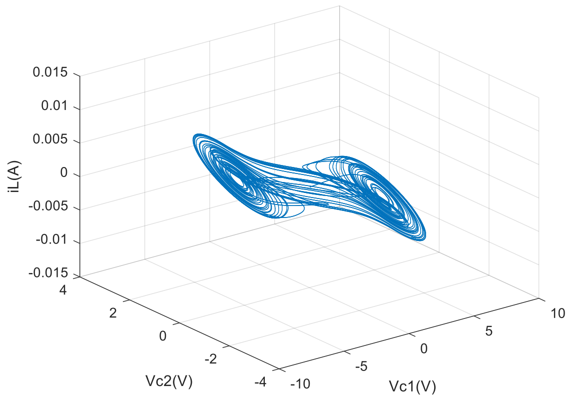
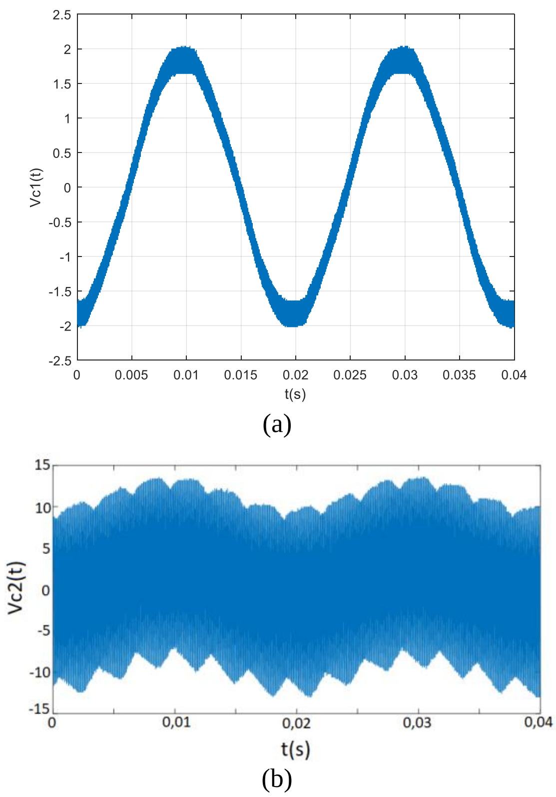
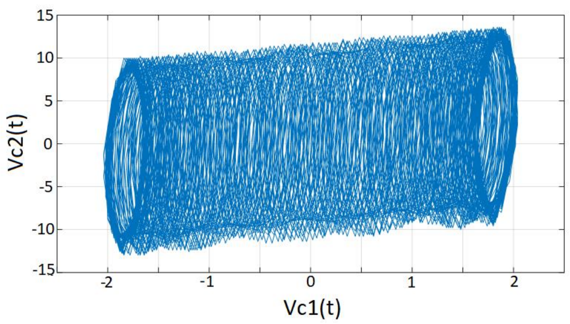


Figure 14. Phase portrait of the circuit drawn in three dimensions.

7. Experimental Results

The circuit is assembled on a board and its experimental waveforms are acquired and shown in Figures 15. The waveforms show chaotic behavior and the double scroll and strange attractors can be seen in Figure 15. However, due to JFET, Schottky diode, and resistor tolerances, the simulated and experimental waveforms do not resemble each other. The effect of the tolerances on the circuit waveforms and their behavior may be inspected in a future study.





(c)

Figure 15. a) V_{c1} vs. t, **b)** V_{c2} vs. t, **c)** V_{c2} vs. V_{c1}

8. Conclusions

In literature, Chua's circuit has been made using different types of Chua's diodes. In this paper, it has been shown that a Chua diode can be made using n-type JETs and Schottky diodes. The combined characteristic of the elements is quite similar to the PWL Chua's diode characteristic. The formulas necessary to calculate the desired parameters of the new Chua's diode, m_o and m_1, are given for chaotic behavior of the circuit and circuit parameters. The circuit can be used to examine chaos in research and education purposes. The effect of the tolerances on the circuit waveforms and their behavior may be examined in a future study. As a future work, we also suggest that the circuit can also be modified to tune parameters of the Chua's diode using V_{GS} voltage of the JFET to obtain different chaotic behavior.

Declaration Of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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