ELectronics EXpress

Controlling high-frequency chaos in resonant tunneling chaos generator circuits

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Abstract: Controlling chaos signal patterns at 12 GHz was demonstrated on the resonant tunneling chaos generator circuit. This was made possible by implementing the reset switch, which resets the circuit to various initial conditions periodically. The reset period was set so short that the initial condition errors can not grow significantly. Thus the circuit repeated identical signal patterns, and they can be clearly observed by a sampling oscilloscope. The application of this circuit to fabricate ultrahigh speed pulse pattern generator was also discussed in this paper.

Keywords: resonant tunneling, chaos, MMIC, HEMT, InP

Classification: Electron devices

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DOI: 10.1587/elex.2.368
Received May 24, 2005
Accepted June 07, 2005
Published June 25, 2005

IEICE Electronics Express, Vol.2, No.12, 368–372

1 Introduction

Resonant tunneling diodes (RTDs) are attracting much attention for high frequency analog and digital applications [1]. Besides their high frequency potential, one of the most important features of the RTDs is a strong nonlinearity in their current-voltage characteristics, which exhibits a negative differential resistance (NDR). Based on this feature, we have proposed a resonant tunneling chaos generator circuit, and also a frequency divider based on the bifurcation phenomenon in this chaos system [2]. High frequency operations up to 88 GHz have been already demonstrated for this frequency divider [3].

The chaos itself is also attractive for various applications, because relatively simple circuits can generate complex signal patterns [6]. As a first step to develop applications of high-frequency chaos, we have tried to observe chaos signals directly in a microwave frequency range. Non periodic high frequency signals such as chaos are difficult to observe, since one can use a sampling oscilloscope. By implementing a periodic reset circuit we have recently succeeded the direct observation of chaos signals at 4 GHz [4]. This technique can be a basis for controlling the high frequency chaos, and hence for various applications. Here, we report an extension of this technique to extract various signal patterns from a high-frequency chaos circuit, and discuss possible applications of this technique.

2 Controlling the RTD chaos generator circuit

Chaos is often regarded as a random and uncontrollable phenomenon. It is, however, deterministic and can be controlled in a limited time. The unpredictability of chaos is a result of system's strong sensitivity to the initial condition, i.e., a small difference in the initial condition grows rapidly with time. Therefore, it is possible to predict the behavior of the chaos system, and also to control it, if one limits the time so short such that the effect of the initial-condition error does not grow significantly.

Fig. 1 shows an example of the controllable chaos circuits, which we discuss in this paper. The basic operation of this circuit has been previously reported [2, 4]. Here, we will briefly describe the circuit operation. This circuit is a kind of van der Pol oscillator having an input terminal. It outputs various types of signal patterns including chaos, when an external oscillating signal with a dc bias is applied.

This circuit is ruled by the set of equations shown below if one ignores the voltage dependence of the RTD capacitance, and parasitic elements.

$$\frac{dI_{\mathrm{L}}(t)}{dt} = \frac{V_{\mathrm{in}}(t) - V_{\mathrm{out}}(t)}{L}, \tag{1}$$

$$\frac{dV_{\mathrm{out}}(t)}{dt} = \frac{I_{\mathrm{L}}(t) - I_{\mathrm{RTD}}(t)}{C_{\mathrm{out}}}, \tag{2}$$

$$V_{\mathrm{in}}(t) = V_0 + A\sin(2\pi f_{\mathrm{in}} t) \tag{3}$$

Here, $I_{\mathrm{RTD}}(V)$ is the $I-V$ curve of the RTD. This is one of the simplest equation set yielding chaos (2nd order ordinary differential equation with an

DOI: 10.1587/elex.2.368
Received May 24, 2005
Accepted June 07, 2005
Published June 25, 2005

IEICE Electronics Express, Vol.2, No.12, 368–372

oscillating extra force). Though a sinusoidal extra force is used in Eq. (3), similar behavior can be observed for input having different waveforms [5].

To force the circuit to return to the certain initial condition repeatedly, we added an extra transistor to the output node, V_{out}, which works as a reset switch. Here, the source of the switch is connected to an external voltage source, different from the previous report [4], where the source was grounded. This permits us to control the initial value of the V_{out}.

However, this can control only one initial value of the 2nd order differential equation. Since direct control of the $\frac{dV_{\mathrm{out}}}{dt}$, or identically I_{L}, is difficult, we tried to control the circuit by a phase of the reset, θ. The θ is defined as a phase of the input signal when the reset pulse turns off. This is effective, though it is not mathematically equivalent to set $\frac{dV_{\mathrm{out}}}{dt}$. Circuit simulation under practical conditions (e. g., limited observation time, limited accuracy of the initial values) revealed that one can select a lot of signal patterns by choosing a set of values $(V_{\mathrm{out}}, \theta)$.

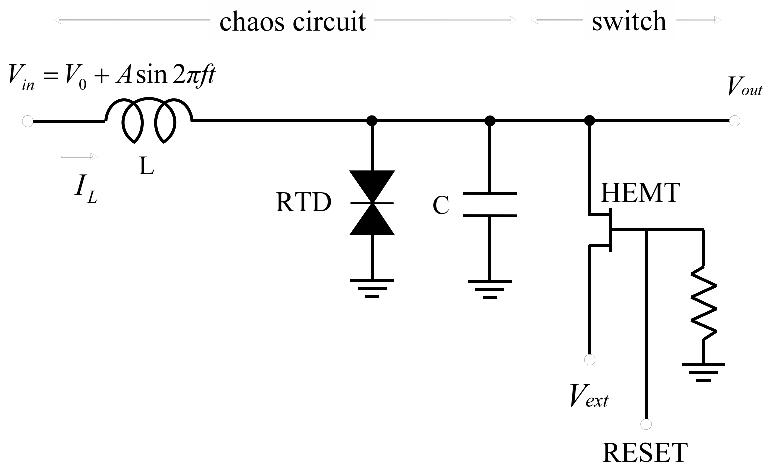

Fig. 1. Resonant tunneling chaos circuit with a reset switch.

3 Results and discussion

The circuit was fabricated on an InP substrate using RTD/HEMT integration technology. The epitaxial structure consists of RTD and HEMT structures. Between them InP etch stop layer was inserted. Moreover the InP gate-recess etch-stopper was also used in the InAlAs barrier layer of the HEMT. These InP etch stop layers ensure good uniformity and reproducibility of the HEMT threshold voltage [7]. The structure was grown by MBE having a cracking cell to grow InP layers. The fabricated RTD has a peak current density of $1 \times 10^5\,\mathrm{A/cm^2}$ with the p/v ratio of 10. The RTD area was $3\,\mu\mathrm{m}^3$. The gate length of the HEMT was $1.2\,\mu$m, and the gate widths were 20 and 200 μm for the output buffer and reset switch, respectively. The characteristic frequency of the circuit was designed to be 5.5 GHz, which was about twice as that in the previous paper [4]. We added the open-drain type output buffer to the

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Received May 24, 2005
Accepted June 07, 2005
Published June 25, 2005

IEICE Electronics Express, Vol.2, No.12, 368–372

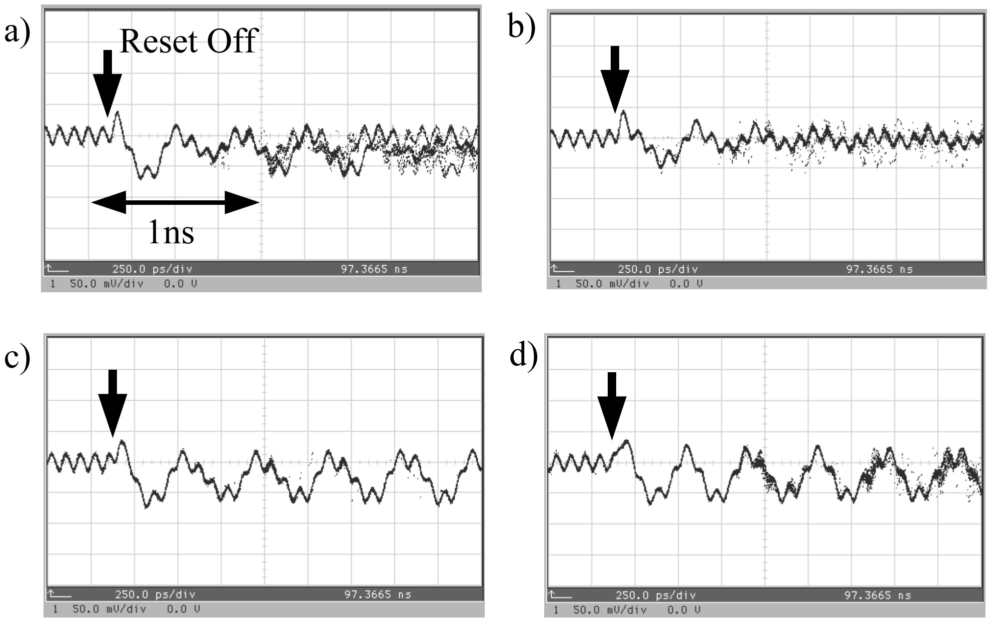

Fig. 2. Output waveforms of the chaos circuit. Arrows indicate the time when reset turns off. (a) $V_{\mathrm{ext}} = 0.35\,\mathrm{V}$, $T_{\mathrm{d}} = 0\,\mathrm{ps}$. (b) $V_{\mathrm{ext}} = 0.30\,\mathrm{V}$, $T_{\mathrm{d}} = 0\,\mathrm{ps}$. (c) $V_{\mathrm{ext}} = 0.30\,\mathrm{V}$, $T_{\mathrm{d}} = 21\,\mathrm{ps}$. (d) $V_{\mathrm{ext}} = 0.30\,\mathrm{V}$, $T_{\mathrm{d}} = 42\,\mathrm{ps}$.

node V_{out} to avoid interference with measurement systems.

The measurement setup was similar to that in the previous report [4] except that the reset switch was connected to the external voltage source. Both the input oscillating signal and the reset pulse were generated by a pulse pattern generator, Anritsu MP1761C, so that the jitter between the input and reset can be minimized. As a result, rectangular oscillating wave was used for the input.

Fig. 2 shows the output waveforms observed with a sampling oscilloscope. The input frequency was 12 GHz. In the figures, an arrow indicates the time when the reset pulse turns off. After this point, the circuit outputs chaotic signals. Apparently random signal patterns are obvious after this point during 10 to 20 periods of the input sinusoidal signal. This indicates that the circuit outputs identical signals due to the periodic reset. The interesting feature of these figures is that the output waveform is blurred after these periods, and it changes into the superposition of various signals. This is the result of the small errors in the initial condition, which grow exponentially with time.

Fig. 2 also demonstrates the controllability of the circuit. The upper two figures (a, b) show the effect of the external voltage. As seen in the figure, the waveform changes by changing the external voltage from 0.35 V to 0.30 V. Next, Figs. (b, c, d) show the effect of the timing of the reset. The external voltage was fixed at 0.30 V, and the phase of the input oscillating signal at the reset falling edge was changed by changing the delay time of the reset pulse from 0, 21, 42 ps. This delay time difference corresponds to the

DOI: 10.1587/elex.2.368
Received May 24, 2005
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phase difference of $\frac{\pi}{2}$ for the input oscillating signal. The output wave form changes with changing the phase. These results demonstrate that various signal patterns can be chosen by controlling the set of values (V_{ext}, θ).

Finally, we will discuss an application of this circuit. Chaos can be regarded as a source of infinite signal patterns. With improvement of the above technique, desired signal patterns can be chosen from the chaos circuit. An example of the applications of this technique is shown in Fig. 3. This is a pulse pattern generator. The required signal patterns are selected by the control circuit, and the signal is digitized by the DFF. If n-bit signal patterns can be selected from the chaos circuit, the clock frequency of the control circuit is only $1/n$ of the input clock signal. Consequently, using RTD chaos circuit, an extremely high frequency pulse pattern generator should be realized. It should be noted that the high speed DFF can be implemented by the resonant tunneling logic gate MOBILE [1].

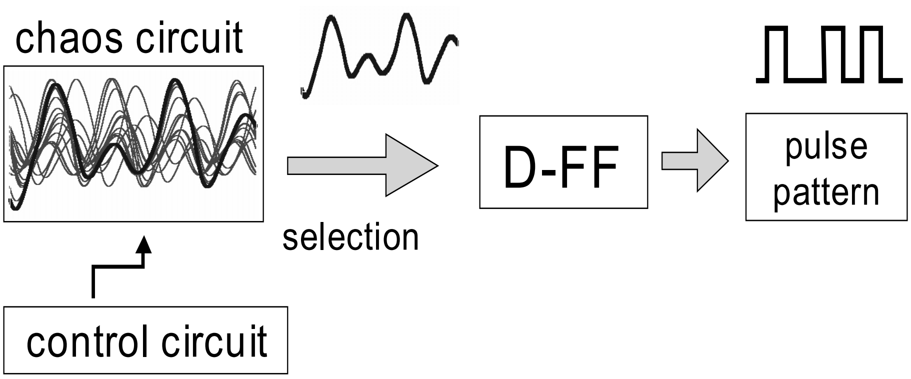

Fig. 3. Output waveforms of the chaos circuit.

4 Conclusion

Control of the resonant tunneling chaos generator circuit was demonstrated at 12 GHz. In order to control the circuit, we introduced periodical reset switch with an external voltage source. Moreover, we proposed a technique to control another initial value of the 2nd order differential equation; the control of the reset phase (timing). The validity of the proposed technique was demonstrated in a fabricated circuit. This technique should be useful to fabricate ultrahigh speed pulse pattern generator.

Acknowledgments

This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology, under contract No. 15360187, by SCAT, NTT and also by VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Cadence Design Systems, Inc.

DOI: 10.1587/elex.2.368
Received May 24, 2005
Accepted June 07, 2005
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