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Electronic Chaos in Silicon Thyristor

Yoh YASUDA and Koichiro HOH†*

Faculty of Engineering, Yokohama National University
156 Tokiwadai, Hodogaya-ku, Yokohama 240, Japan
† Faculty of Engineering, the University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

Chaotic behaviors were observed in ac response of the silicon thyristor in relation to its S-shaped negative differential conductivity. Both period-doubling and intermittent types of chaos appeared in the same device corresponding to different sets of operating parameters. A simple device/circuit model was sought to describe chaos in such kinds of bistable semiconductor devices.

1. INTRODUCTION

Recently, understanding of complicated systems has made remarkable progress in physics and mathematics. Typically, extensive studies are being made on the chaos (deterministic chaos), the phenomenon in which a certain system shows unpredictable behavior although it is rigorously described by nonlinear differential equations[1].

In the fields of electronics[2], circuits which contain negative-resistance devices like a neon tube together with the elements L or C are known to behave chaotic[3]. However, little studies have been made concerning chaos in semiconductor devices without external L nor C. Only reported are the studies from physics point of view, e.g., the impact ionization in GaAs[4] and in the magnetic freeze-out in Si[5], both with low-temperature bulk samples without junctions.

We have first observed several aspects of chaos in the ac response of Si thyristors. The reason why we tried the thyristor was that it is most developed and stable among those which exhibit negative differential conductivity (NDC), usable at room temperature, and its S-shaped NDC is controlled by the gate current. We have also tried to interpret the chaotic nature by a simple device/circuit model.

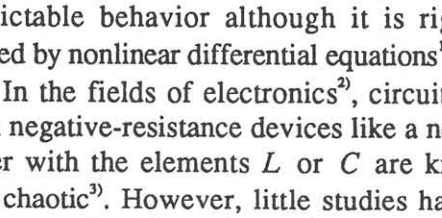

Fig.1 Measurement circuit

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the circuit for the observation of chaos in a thyristor. A large amplitude ac voltage $V = V_o \sin(2\pi f t)$ was fed through the load resistor R_L to the anode of a thyristor, typically 2SF101 (NEC) of small-power type. Anode dc bias V_{bias} was included. These voltages were selected so as to cover the NDC region of the device characteristics in the forward half cycle and to ensure that the device was turned-off in each reverse half cycle. The breakover voltage V_{BO} (initiation of turn-on) of the thyristor was set to a predetermined value by changing the dc gate current I_g. Figure 2 shows a typical dc characteristics of the device used in this experiment.

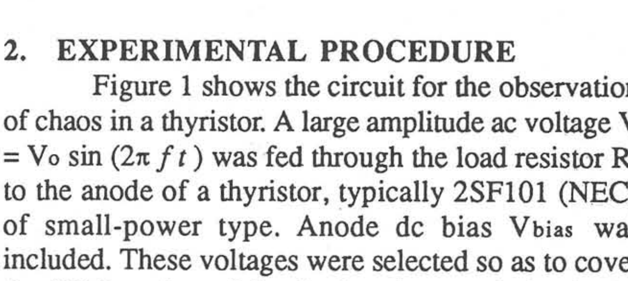

Fig.2 Measured dc characteristics of 2SF101

* *To whom inquiries should be addressed.*

In the ac measurement, the voltage drop V_{ak} between anode and cathode was recorded in a digital oscilloscope and was analyzed by a personal computer.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 3 shows the change of V_{ak} waveform as I_g was increased, keeping the frequency f constant at 10kHz. At $I_g = 4.8\mu A$, V_{ak} turned to have period $2T$ (where T is the period of the ac source voltage) as shown in Fig.3(a), then period $4T$ appeared at $I_g = 5.2\mu A$ (Fig.3(b)). The frequency components $1/2f$ and $1/4f$ are clearly seen in corresponding Fourier spectra. Beyond $I_g = 6.5\mu A$, V_{ak} showed chaotic behavior where the waveform lost periodicity and the Fourier spectrum contained diffuseness.

To ascertain that the waveform is chaotic, successive peaks V_n in Fig.3(c) were plotted in a space (V_n, V_{n+1}), known as Lorenz plot, which mathematically means the first return map. As shown in Fig.4, the plot showed single-valued function which is characteristic of chaos. Proofs as chaos were further reinforced by determining Lyapunov exponent[6] λ as positive ($\lambda = +0.39$) from the curves in Lorenz plot and the attractor dimension[6] D as fractal ($D = 1.23$).

Figure 5 is the map of regions of the parameters f and I_g where the V_{ak} waveform with periods $1T$, $2T$, $4T$, ... and chaos appeared. In Fig.6, the peak values of V_{ak} were traced as f was continuously changed. This clearly shows a pitchfork type, period-doubling bifurcation from $1T$ to $2T$, $4T$, $8T$ and finally chaos. In the same device, we have also found an intermittent chaos when a different V_{bias} was selected[7].

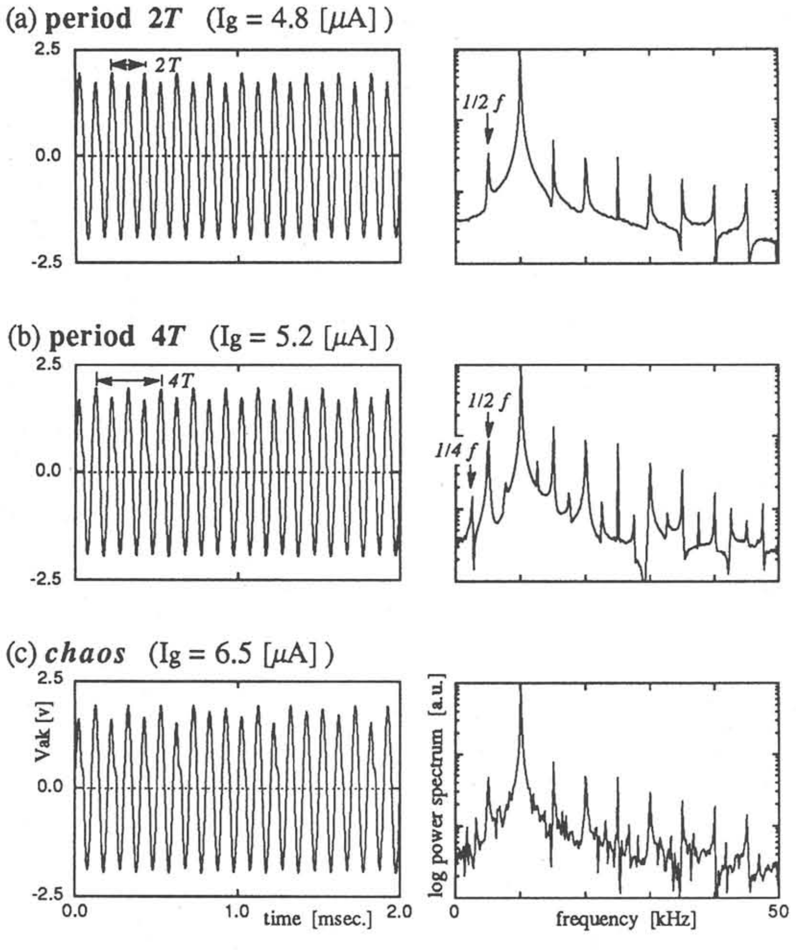

Fig.3 Waveforms and Fourier-spectra
(f = 10.0 [kHz], Vo = 2.5 [v], Vbias = 0 [v], $T = 1/f$)

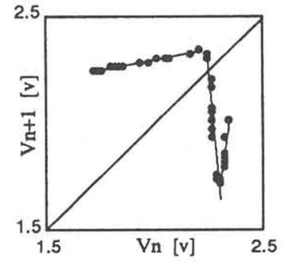

Fig.4 Lorenz Plot

First return map made from n th and (n+1)th maximal values of a chaotic waveform

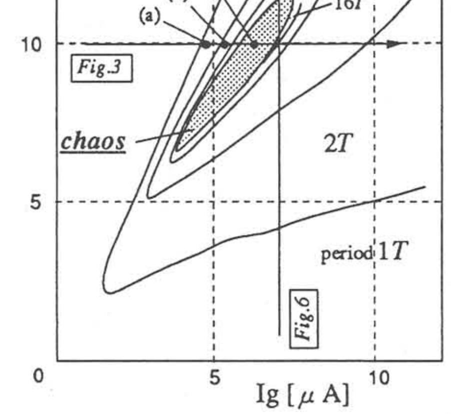

Fig.5 2-dimensional phase diagram

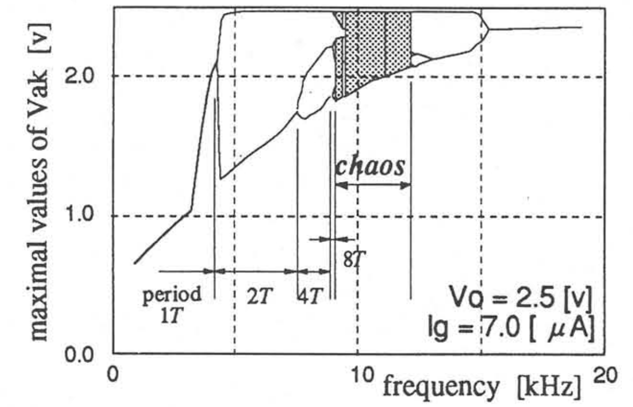

Fig.6 Bifurcation diagram
1-dimensional phase diagram
taken along the vertical arrow in Fig.5

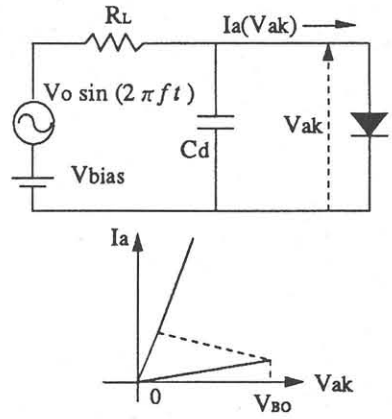

Fig.7 A model for simulation

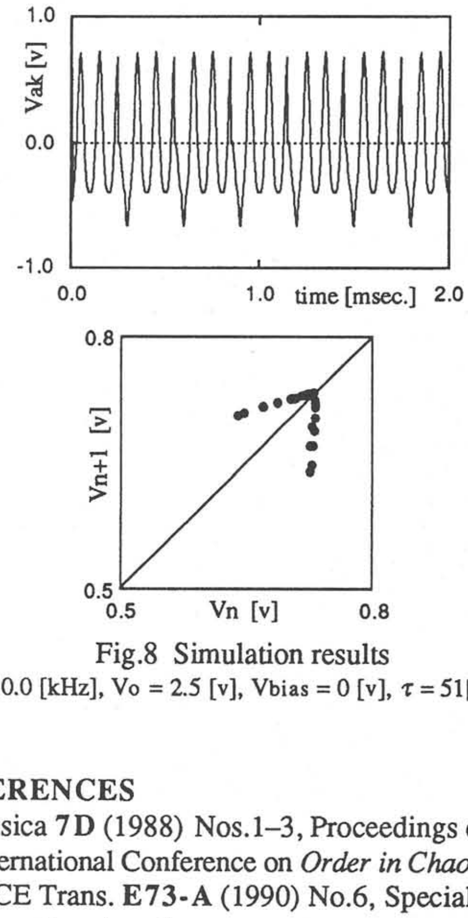

Fig.8 Simulation results
(f = 10.0 [kHz], Vo = 2.5 [v], Vbias = 0 [v], τ = 51[μsec.])

4. SIMULATION WITH A MODEL

We attempted to explain these chaotic behaviors by the model shown in Fig.7. The thyristor was expressed as a combination of a depletion layer capacitance Cd of the junction which breaks down at the initiation of turn-on, and a diode whose NDC characteristics were approximated by a piecewise-linear function as shown in the figure. Ig was taken simply as a parameter which determined V_{BO} and the gate circuit was omitted. Cd was assumed dependent on Vak as $Cd = A(\Phi_D+V_{ak})^{-1/2}$ where Φ_D is the diffusion potential and A is a constant. A delay time τ was assumed to elapse before the device turned-on after Vak reached V_{BO}.

One of the results of calculation with this model is shown in Fig.8. Concave-curved Lorenz plot agrees semi-quantitatively with our experiment, but the tendency in the output waveform and matching of some parameters to actual ones are the problems to be solved by improving the present model.

5. CONCLUSION

Chaotic behavior was first observed in the response of the silicon thyristor when its anode was excited by an ac source. The same device exhibited both period-doubling and intermittent types of chaos corresponding to the different sets of control parameters f, Vo, and Ig.

These behaviors were partly explained through a simple device/circuit model which takes a junction capacitance and static I-V characteristics of the thyristor into account. The chaos in thyristors suggests the utility of similar bistable devices in realizing novel data processing system like chaotic neural network[8].

REFERENCES

1) Physica **7D** (1988) Nos.1–3, Proceedings of the International Conference on *Order in Chaos*.
2) IEICE Trans. **E73-A** (1990) No.6, Special issue on engineering chaos.
3) M.P.Kennedy and L.O.Chua: IEEE Trans. **CAS-33** (1986) 974.
4) K.Aoki and K.Yamamoto: Appl.Phys. **A48** (1989) 111.
5) K.Yamada, N.Miura and C.Hamaguchi: Appl.Phys. **A48** (1989) 149.
6) H.Nagashima: Buturi **41** (1986) 19. [in Japanese]
7) Y.Yasuda and K.Hoh: IEICE Trans. **E76-A** (July 1993)
8) K.Aihara, T.Takabe and M.Toyoda: Phys.Lett. **144A** (1990) 333.