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Origin of Chaos in Thyristors

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Electronic chaos in thyristors was observed by exciting the anode of thyristors with ac signal. The origin of this chaotic phenomenon was revealed by detailed measurement of p-base potential, measurement with 2-transistor structure and SPICE simulation. Chaos was generated by return-mapping nature in the variation of p-base potential. Chaotic behavior in thyristor was also reproduced in the experimental coupled-transistor structure and SPICE simulation.

1. Introduction

Miniaturization of MOSLSIs have been proceeded to realize high speed and high integration of VLSIs[1]. In addition to this trend, many proposals are presented recently for realizing a multi-functional device with a simple structure for the generation beyond the limit of miniaturization.

Deterministic chaos, the complexity generated in simple nonlinear systems, is studied in various fields for the last decade[2], and several applications for information-processing utilizing the controllable complexity of chaos have been proposed.

Electronic chaos in thyristors was observed by our group by exciting the anode of thyristors with ac signal[3,4]. When a thyristor is driven at a high frequency near its response limit, with sufficient gate current for turn-on, the thyristor is turned on not in every positive half cycle of the supplied voltage but with various periods, or shows non-periodic behavior depending on the circuit parameters. Chaos in a thyristor shows various types, period-doubling, period-adding and intermittent types, and their appearance can be easily controlled by the selection of parameters.

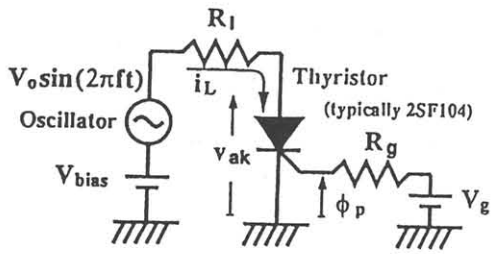


Fig. 1. Measurement circuit with a thyristor.

In this report, we analyze the mechanism of chaos in thyristors from detailed measurements of the potential at the p-base of thyristor and from the results of SPICE simulation.

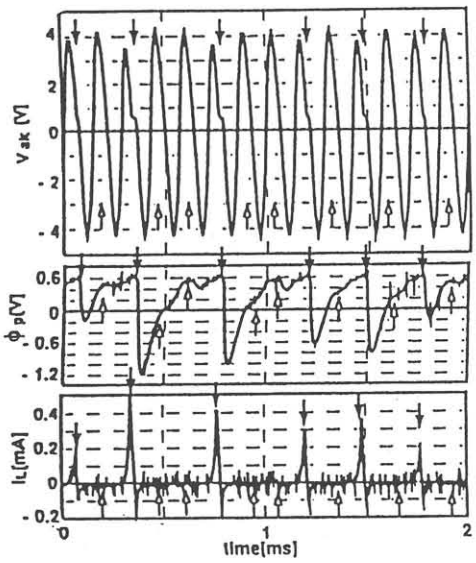
2. P-Base Potential

Besides the change in anode-cathode voltage V_{ak}, which we have previously reported[3,4], we measured the potential ϕ_p at the p-base to which the gate terminal is connected. The measurement circuit is shown in Fig.1. Measured V_{ak} and ϕ_p in chaotic state (Fig.2) denotes that the chaotic behavior of V_{ak}, or seemingly random occurrence of turn-on, is governed directly by ϕ_p.

ϕ_p is raised gradually by gate current in the forward half cycle and falls deep by reverse current at turn-off process in the reverse half cycle. Turn-on of thyristor starts when ϕ_p reaches to a threshold, and never occurs if ϕ_p is below it.

Moreover, ϕ_p fall is larger in the reverse half cycle as ϕ_p peak in the previous half cycle was larger and reached to the threshold faster. This is caused by the larger reverse current; it is the reflection of the amount of charge in the p- and n-base in the thyristor supplied in turn-on process.

This mechanism is explained as below. When the emitter junction of the intrinsic npn-transistor



(↓ turn-on, ↑without turn-on)

Fig. 2. Measurement results of V_{ak}, ϕ_p and i_L with the thyristor circuit shown in Fig. 1.

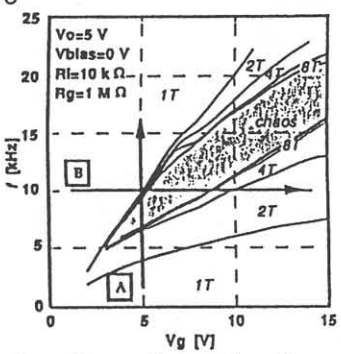
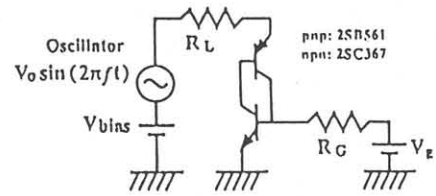


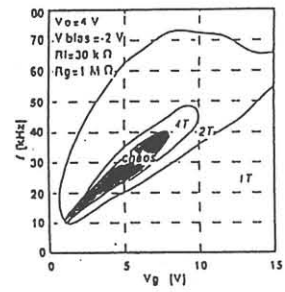
Fig. 3. Two-dimensional parameter space of gate voltage V_g and oscillation frequency f, obtained by the circuit in Fig. 1.

which consists a part of the thyristor is reverse biased deeply, gate current is used to charge this junction and so ϕ_p rises gradually. When ϕ_p reaches to the threshold voltage, the collector current flows and supplies charge in the n-base region of the pnp-transistor. In this case, the supplied charge must be drained to the anode electronode by the reverse current through three serial junctions in the following reverse half cycle, and the same quantity of charge is drained from the p-base region and so ϕ_p falls deep depending on the charge supplied in the n-base region.

Figure 3 shows the parameter space of gate bias V_g and oscillation frequency f which result in periodic or chaotic state. Sweeping f along the Line A from low- to high- frequency, period 1T,2T,4T,... and chaos appears successively ($T = 1/f$), and returns



(a)



(b)

Fig. 4. (a) Measurement circuit with the coupled transistors structure. (b) Two-dimensional parameter space of (V_g, f) obtained by Fig. 4(a).

to periodic state at higher frequencies. This is a typical example of period-doubling chaos.

At low f, the positive period of the supplied voltage is long enough for the n- and p-base region of the thyristor to be saturated by the positive feedback current in the thyristor. In this case, the charge in the n- and p-base region take constant values determined by the external circuit, the load resistance R_L and the supplied voltage V_o. Therefore ϕ_p falls to a constant voltage and the thyristor shows periodic behavior, including period multiplication.

At high-enough f, the quantity of charge supplied in the n-base region is small because the positive period of the supplied voltage is short. Therefore the fall of ϕ_p is small and equilibrates with the rise of ϕ_p by the gate current, so the thyristor also shows periodic behavior.

The chaotic behavior is observed when the thyristor is driven in the intermediate frequency region where the value of ϕ_p are varying depending on its state in the previous half cycle. This return-mapping process can cause chaos in this frequency region.

3. Measurements with Coupled Transistor Structure

As revealed above, chaos in a thyristor is caused by the variation of the p-base potential, not by the characteristic nature of pnpn structure such as avalanche breakdown. This is proved by the measurement with the coupled pnp- and npn-transistor

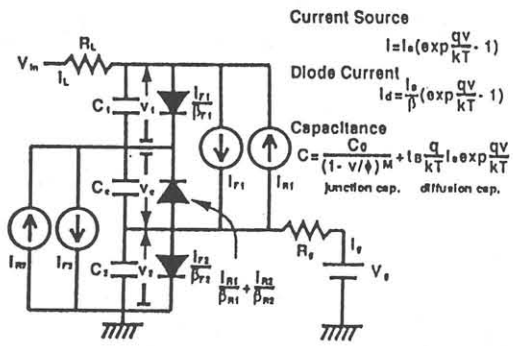


Fig. 5. Model for the experimental thyristor circuit in Fig. 1.

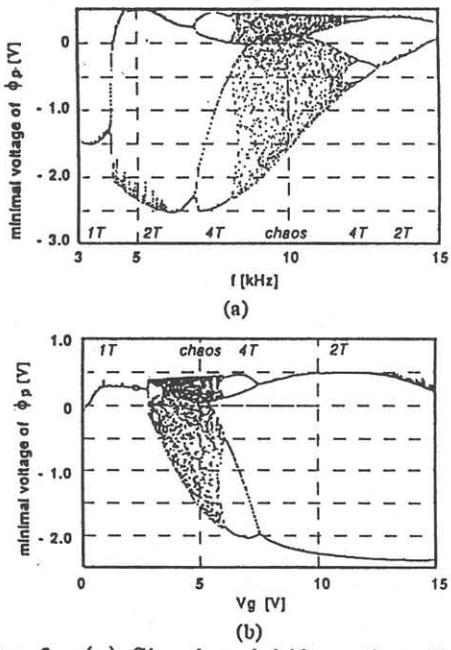


Fig. 6. (a) Simulated bifurcation diagram along line A in Fig. 3. (b) Along line B.

structure as shown in Fig.4(a),(b). The parameter region where chaotic behavior is observed is shifted to higher f because the response time of a transistor is generally faster than that of a thyristor. Nevertheless, the bifurcation feature observed with the coupled-transistor structure has the same tendency as period-doubling chaos observed with the thyristor. This indicates that the chaos can be generated with the coupled transistor structure in integrated circuits, not necessarily with a discrete thyristor, in the future application of the chaotic phenomena.

4. SPICE Simulation

Figure 5 is the equivalent circuit for the present thyristor experiment. The thyristor is replaced by coupled pnp-npn transistors, and each transistor is expressed by Gummel-Poon's equivalent circuit corresponding to SPICE model[5]. The capacitances in Fig.5 are the components of junction- and diffusion-capacitances. The bifurcation phenomena in the experiment are simulated with SPICE simulator as shown in Figs.6(a) and 6(b). They correspond to scanning along line A and line B in Fig.3 respectively. The feature of bifurcation of the simulated results has a good agreement with that of the experimental results. Namely, it indicates that the return-mapping nature which is essential for the generation of chaos is inherent in the characteristics of this equivalent circuit and that the chaos in thyristors is general phenomenon with thyristor structure, not by the non-linearity of the external components of the circuit. The analytical expression of the first return-map is being constructed by simplifying this model.[6]

5. Conclusion

When a thyristor is driven by the large amplitude ac signal at its anode, charge/discharge of the p-base region determines the chaotic behavior. The analysis with SPICE of this process based on coupled transistor model well reproduced chaotic features measured with a thyristor and with coupled two-transistor structure. This indicates that the chaotic behavior can be realized with general pnpn-structure without any special structure or complicated circuit. The present results encourage us to design novel devices which utilizes bifurcation and chaos in the information processing.

Acknowledgement

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