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TESTA, PEREZ, AND JEFFRIES RESPOND

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### Authors

Testa, J.  
Perez, J.  
Jeffries, C.

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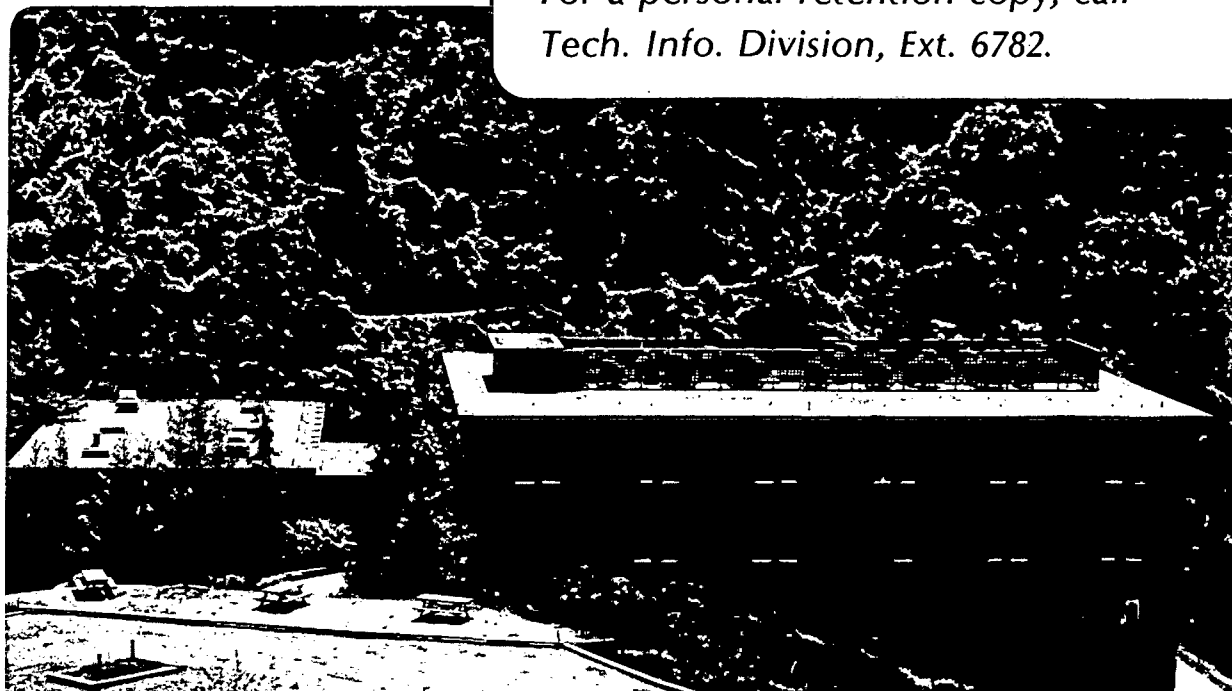
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James Testa, Jose Perez, and Carson Jeffries

June 1982

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TESTA, PEREZ, AND JEFFRIES RESPOND

James Testa, Jose Perez, and Carson Jeffries

Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720

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## RESPONSE TO COMMENT BY E. R. HUNT

TESTA *et al.* RESPOND: The first question we address is: What nonlinear diode properties give rise to the cascade of period-doubling bifurcations in the experiments of Testa *et al.*<sup>1</sup> While confirming our results, Hunt concludes from other experiments that the dominant nonlinearity may be the reverse recovery characteristic rather than the nonlinear capacitance of the diode. Experiments here indicate that no bifurcation is observed: (1) for a varactor diode always reverse biased; (2) for two identical varactor diodes in series back-to-back. This indicates that forward-reverse switching is essential, but does not show that a nonlinear capacitance is not also required. Two types of capacitance are associated with a junction diode:<sup>2</sup> (1) The junction capacitance, dominant under reverse bias, with dependence  $C_j \approx C_{oj}[1+V_d/0.6]^{-0.5}$  on the diode voltage  $V_d$ . (2) The charge storage capacitance, dominant under forward bias, and given by  $C_s \approx C_{os} I_0 \tau_p$ , where  $I_0$  is the diode d-c current and  $\tau_p$  is the minority carrier lifetime, essentially the reverse recovery time. Varactor diodes have abrupt junctions usually with  $C_j > C_s$ ; ordinary rectifier diodes usually have  $C_j < C_s$ . For an LRC circuit the varactor and the rectifier diode should show resonant frequency increasing and decreasing, respectively, with driving voltage; both these effects are observed here. The experiments of Testa *et al.* correspond to the first case. Gibson and Kusnezov<sup>3</sup> have observed period doubling sequences in a rectifier diode, corresponding to the second case.

A general analysis of driven diode dynamics can be made by relinquishing the concept of capacitance and integrating directly with a computer the nonlinear differential equations:  $LI + RI + V_d = V_0 \cos \omega t$ , plus at

least two more integro-differential equations in  $V_d(t)$  and  $I(t)$ , using measured values of parameters  $C_{oj}$ ,  $C_{os}$ ,  $\tau_p$ , etc. The solution could be examined for bifurcation and chaotic behavior, and the relative importance of the parameters determined. This is an interesting and unsolved non-trivial problem.

From another viewpoint, it is not necessary to do this. Instead, we ask a second question more germane to the theory of chaos: Does a complex driven nonlinear diode oscillator behave *as if* it were modelled by a simple one-dimension recursion relation  $x_{n+1} = f(\lambda, x_n)$ .<sup>4</sup> The question is answered in the affirmative by the experiments of Testa *et al.*,<sup>1</sup> Perez and Jeffries,<sup>5</sup> and Jeffries and Perez,<sup>6</sup> for a particular varactor diode (1N953). This system is observed to display the universal chaotic behavior characteristic of a quadratic maximum for  $f(x)$ . The effects of additive noise<sup>5</sup> and observation of intermittency<sup>6</sup> are also in agreement with this assumption. These experiments and interpretations are not invalidated in any way by the above Comment and our Response. Not all diodes can be expected to display this particular route to chaos. It is not yet possible to predict the chaotic behavior for any real physical system, although once it has been experimentally established that a recognized route is being followed, the behavior appears to be universal, independent of the detailed dynamics.

J. Testa, J. Perez, and C. Jeffries  
Materials and Molecular Research Division  
Lawrence Berkeley Laboratory and  
Department of Physics  
University of California  
Berkeley, CA 94720

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- <sup>1</sup>J. Testa, J. Perez and C. Jeffries, Phys. Rev. Lett. 48, 714 (1982).
- <sup>2</sup>B. G. Streetman, Solid State Electronic Devices (Prentice Hall, New Jersey, 1972).
- <sup>3</sup>G. Gibson and D. Kusnezov, private communication.
- <sup>4</sup>M. J. Feigenbaum, J. Stat. Phys. 19, 25 (1978).
- <sup>5</sup>Jose Perez and Carson Jeffries, Phys. Rev. B, in press.
- <sup>6</sup>Carson Jeffries and Jose Perez, submitted for publication.

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