NON-LINEAR DYNAMIC PHENOMENA IN ELECTRON TRANSFER DEVICES

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Abstract
We have modelled the highly non-linear dynamic phenomena which arise in Gunn diodes by interaction between the internally generated domain mode and an external microwave signal. As the frequency of the microwave signal is changed, a devil's staircase of frequency-locked oscillations develops, interspersed with quasiperiodic solutions. Period-doubling and other forms of mode-converting bifurcations can be seen in the interval of some of the steps. At higher microwave amplitudes, deterministic chaos arises. The transitions to delayed, quenched, and limited space charge accumulation modes are followed.

1. Introduction

Instabilities in dissipative systems can give rise to a wealth of complex non-linear phenomena including (i) cascades of period-doubling bifurcations, (ii) frequency-locking between an internally generated oscillation and an external signal, and (iii) various types of deterministic chaos. The study of these phenomena has attracted a rapidly growing interest during the last decade, and examples of chaotic behaviour have been reported for a number of electronic circuits(1), including circuits involving semiconductor devices such as tunneling(2) and varactor diodes(3). In these studies, the active element has usually been characterized by means of a time-independent current-voltage relation. In no case, it appears, has the extended nature of the device or its complex internal dynamics been taken into account.

Based upon a relatively detailed model for the formation and propagation of subsequent high field domains, the present paper describes the highly non-linear dynamic phenomena which can occur in a periodically driven Gunn diode. A map of the distribution of behavioural forms in parameter space is obtained by simulating the model with a large number of different amplitudes and frequencies for the external signal.

2. The Model

It is well-known that n-type GaAs and a number of other compound semiconductors can exhibit self-sustained current oscillations in the microwave range when the applied drift field exceeds a characteristic threshold value[4]. Due to inefficient energy relaxation, the electron gas heats up to very high temperatures, and a transfer of carriers from the high mobility conduction band minimum to a set of low mobility satellite valleys takes place. If this transition is fast enough, a bulk negative differential conductivity may arise[5]. The spatially homogeneous electron distribution then becomes unstable, and propagating high field domains are formed. In the external circuit, the formation and propagation of these domains give rise to current oscillations with a typical frequency of 7-9 GHz for a 12 μm sample.

The Gunn effect has been extensively studied both by simplified analytical methods[6] and by numerical techniques[7]. In particular, Copeland[8] has shown that the presence of a microwave signal of sufficient amplitude and frequency can suppress the domain formation and produce an alternative mode of operation for the Gunn diode which is referred to as limited space charge accumulation (or LSA-) mode.

To understand the dynamics of domain formation and propagation in the presence of a microwave signal we have developed the following model:

The current density $j = j(t)$ is assumed to consist of drift and diffusion terms for each of the two groups of electrons, i.e. electrons in the central conduction band minimum, and electrons in the upper valleys. In addition we have included a displacement term which expresses conservation of charge. Thus

$$j = n_1 e v_1(F) + n_2 e \mu_2 F - eD_{n1}\frac{\partial n_1}{\partial x} - eD_{n2}\frac{\partial n_2}{\partial x} + \varepsilon\frac{\partial F}{\partial t}. \qquad (1)$$

Here $F = F(x,t)$ is the local electric field as determined from Poisson's equation

$$\frac{\partial F}{\partial x} = \frac{e}{\varepsilon}(n_1 + n_2 - n_o). \qquad (2)$$

$n_1 = n_1(x,t)$ and $n_2 = n_2(x,t)$ are the local electron concentrations, with subscript 1 for electrons in the conduction band minimum and subscript 2 for electrons in the upper valleys. e is the elementary charge and ε the static dielectric constant. The relative dielectric constant $\varepsilon_r = 12.5$ for GaAs. The diffusion constants and the upper valley mobility are assumed to be $D_{n1} = 200\ cm^2/s$, $D_{n2} = 8\ cm^2/s$, and $\mu_2 = 320\ cm^2/Vs$, respectively. For the thermal equilibrium electron concentration we have used $n_o = 2 \cdot 10^{15}/cm^3$.

Approximate, analytical expressions for the velocity-field characteristic $v_1(F)$ of the electrons in the conduction band minimum and for the equilibrium fraction $n_{20}(F)/n_o$ of electrons in the upper valleys have been derived from the detailed Monte Carlo calculations reported by Fawcett et al.[9] We have here assumed an intervalley deformation potential of $1 \cdot 10^9$ eV/cm. Intervalley equilibration of the electron distribution is expressed by

$$\frac{\partial n_2}{\partial t} = \frac{n_{20} - n_2}{\tau} \tag{3}$$

with a relaxation time of $\tau = 2 \cdot 10^{-12}$ sec.

As boundary conditions we have used

$$n_1(0,t) = n_o,\ n_2(0,t) = 0 \quad \text{and} \quad n_1(L,t) + n_2(L,t) = n_o \tag{4}$$

where $L = 12\ \mu m$ denotes the length of the sample. To facilitate the domain formation we have assumed that there is a slight (0.1%) enhancement of the specific resistance in that 1% of the crystal which is closest to the cathode end. Finally, we have applied the normalization condition

$$\int_0^L F(x,t)dx = V_{ext} = L \cdot F_{dc}(1 + A\sin(2\pi ft)) \tag{5}$$

where $F_{dc} = 4.0$ kV/cm is the applied dc-field. f and A denote the frequency and relative amplitude of the external microwave signal, respectively.

3. Simulation Results

Simulation with the above model has revealed a large variety of different modes of behaviour, depending upon the values of A and f. As examples the following figures show the 2:1 frequency-locked solution obtained for A = 0.20 and f = 12.5 GHz (fig. 1), the 4:3 frequency-locked solution obtained for A = 0.20 and f = 10.0 GHz (fig. 2), and the chaotic solution obtained for A = 0.56 and f = 30.0 GHz (fig. 3).

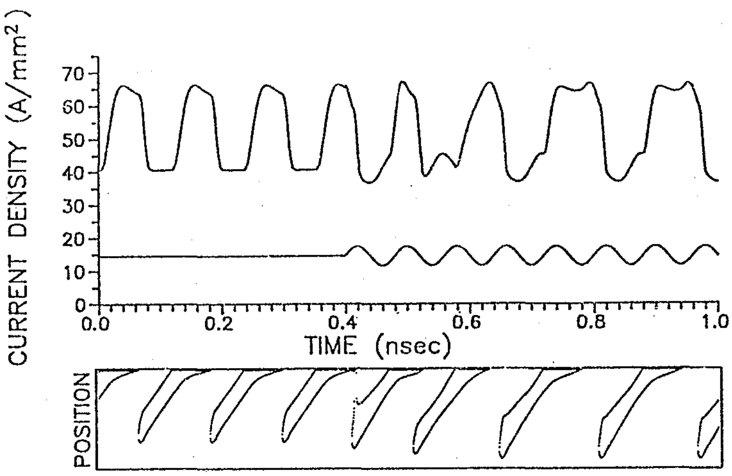

Figure 1. Onset of a 2:1 frequency-locked solution upon application of a microwave signal of amplitude A = 0.20 and frequency f = 12.5 GHz. By comparison with the undisturbed domain mode it is observed how the domains adjust their time of formation and their speed of propagation so as to entrain with the microwave signal. The upper panel shows the temporal variation of the current density and the applied field. The lower panel shows the propagation of domains through the crystal.

By means of a large number of simulations we have determined how the type of solution varies with the amplitude and frequency of the applied microwave signal. This has provided the phase diagram in figure 4. In this diagram, Arnol'd tongues of frequency-locked behaviour are seen to arise in intervals around all rational ratios of the external frequency to the internally controlled domain frequency. Most evident are the 1:1, 2:1, 3:1, 4:1, 5:1, and 6:1 tongues. Between these tongues there are tongues where 3:2, 5:2, 7:2, 9:2, 5:3, etc. entrainment takes place.

With increasing microwave amplitudes, the tongues broaden. Since it is easier to delay domain formation and to reduce the speed of domain propagation than to speed-up these processes, the broadening is most significant on the low-frequency side of the tongues. In the region

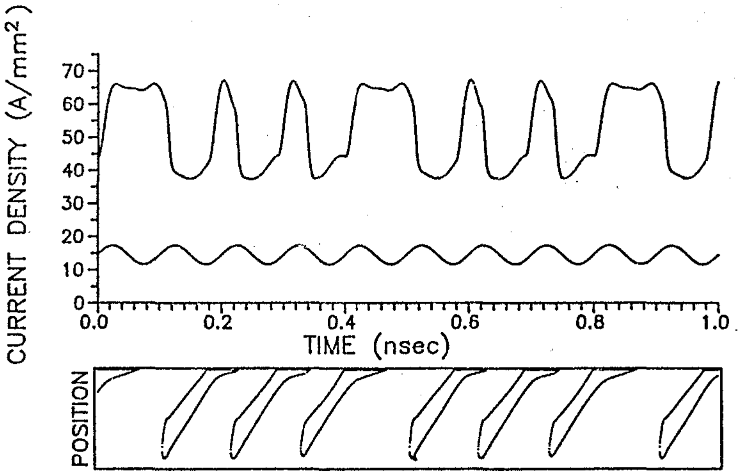

Figure 2. Stationary 4:3 frequency-locked solution obtained for A = 0.20 and f = 10 GHz. To keep in step with the microwave signal, the domain mode must delay the formation of every third domain.

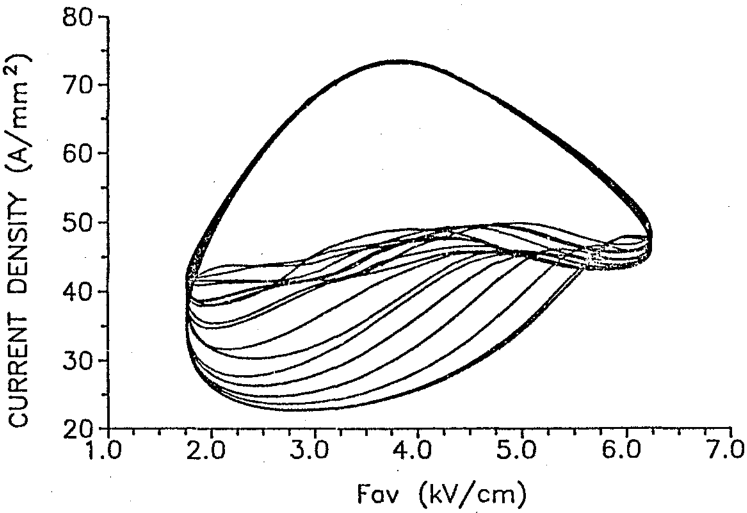

Figure 3. Phase-plot of the chaotic solution obtained for A = 0.56 and f = 30.0 GHz. In the neighbourhood of this solution we find a variety of complex solutions produced by period-doubling and mode-conversion of simpler frequency-locked solutions.

where the tongues start to overlap, various forms of period-doubling and mode-converting bifurcations take place. A more detailed investigation of the region between the 3:1 and 4:1 tongues, for instance, has revealed the existance of 13:4, 10:3, 14:4, 7:2, 11:3, and 8:2 frequency-locked solutions.

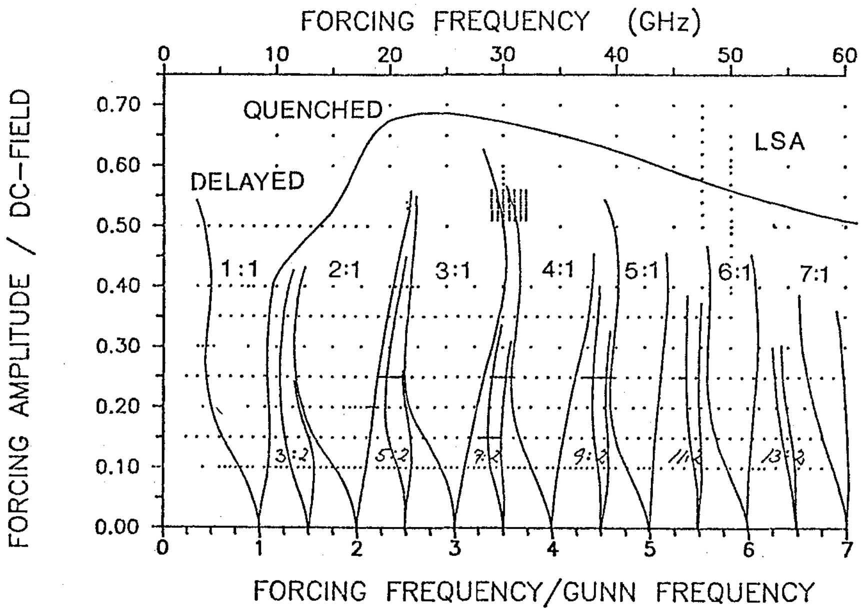

Figure 4. Phase diagram showing the distribution of behavioural forms as function of the frequency and amplitude of the applied microwave signal. Interspersed with the Arnol'd tongues of frequency-locked behaviour one can find quasiperiodic solutions.

As the microwave amplitude approaches 60-70% of the applied drift field, a transition to delayed and quenched domain modes occurs at relatively low microwave frequencies while at higher frequencies LSA-mode is obtained.

4. Conclusion

A closer examination of the interaction between the internally generated domain mode and an external microwave signal in GaAs Gunn diodes has revealed the existence of a great variety of complex non-linear dynamic modes of behaviour. While on one hand illustrating the universal phenomenon of entrainment in non-linear dynamic systems, the details of the Arnol'd tongues also reflect the parameters of the model in a relatively sensitive manner. One of the parameters which is most difficult to obtain experimentally is the intervalley scattering time. By comparison with our numerical calculations, experiments with periodically driven Gunn diodes may thus be useful in determining of this parameter.

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References

1. Matsumoto, T., L.O. Chua, and M. Komuro: "The Double Scroll", IEEE Trans. on Circuits and Systems CAS-32, p. 798 (1985).
2. Pikovsky, A.S., and M.I. Rabinovich: "Stochastic Oscillations in Dissipative Systems", Proc. Int. Workshop on Nonlinear and Turbulent Processes in Physics, Physica D2, p. 8 (1981).
3. Feingold, M., D.L. Gonzalez, O. Piro, and H. Viturro: "Phase Locking, Period Doubling, and Chaotic Phenomena in Externally Driven Excitable Systems", Phys. Rev. A37, p. 4060 (1988).
4. Gunn, J.B.: "Microwave Oscillations of Current in III-V Semiconductors", Solid State Comm. 1, p. 88 (1963).
5. Ridley, B.K.: "Specific Negative Resistance in Solids", Proc. Phys. Soc. (London) 82, p. 954 (1963).
6. Butcher, P.N., W. Fawcett, and C. Hilsum: "A Simple Analysis of Stable Domain Propagation in the Gunn Effect", Brit. J. Appl. Phys. 17, p. 841 (1966).
7. McCumber, D.E., and A.G. Chynoweth: "Theory of Negative-Conductance Amplification and of Gunn Instabilities in Two-Valley Semiconductors", IEEE Trans. on Electron Devices ED-13, p. 4 (1966).
8. Copeland, J.A.: "A New Mode of Operation for Bulk Negative Resistance Oscillators" , Proc. IEEE 54, p. 1479 (1966).
9. Fawcett, W., A.D. Boardman, and S. Swain: "Monte Carlo Determination of Electron Transport Properties in Gallium Arsenide", J. Phys. Chem. Solids 31, p. 1963 (1970).