

INVESTIGATIONS ON THE DYNAMICS OF A METAL-FERROELECTRIC-SEMICONDUCTOR HETEROSTRUCTURE

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A series RLC electric circuit with the metal-ferroelectric-semiconductor (MFS) heterostructure playing the role of nonlinear capacity shows various nonlinear dynamics such as period doubling and Ruelle-Takens scenarios of evolution to chaos. In this paper we present preliminary experimental investigations and theoretical analysis on the dynamics of this structure. We focus only on a period-doubling bifurcation evolution to chaos induced by the change in the amplitude of a sinusoidal driving. A theoretical model of MFS structure as nonlinear element of an electrical circuit justifies a model of two coupled nonlinear Duffing oscillators. The model takes into consideration the presence of two types of nonlinearities. The first, originating in the switching of the ferroelectric domains is treated in the framework of Landau phase transition theory and the second, originating in the asymmetry of the semiconductor surface potential as function of the charge density, is considered in the classical theory of MOS structures. The dynamics of the theoretical model are in reasonable agreement with the experimental results.

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1. Introduction

In solid state physics, one of the fields in which chaotic behaviour has been evidenced involves ferroelectric materials. The ferroelectric domain switching has been modelled using different approaches both theoretical [1] and more empirical [2]. Nevertheless, these models are not capable to describe the switching process correctly [3-4].

Nonlinear series analyses were performed on triglycine sulphate (TGS) [4-5] and KH_2PO_4 (KDP) [6-7] ferroelectric materials. The nonlinear behaviour was treated in the framework of Landau theory, which qualitatively explains the presence in the ferroelectrics of two different states of spontaneous polarization related to each other by reflection symmetry. The investigated physical system consists of an RLC series circuit whose nonlinear component is the ferroelectric capacitor, driven externally by a harmonic voltage source. The mathematical model used for describing the time evolution of the system, based on the Duffing equation reproduces in a satisfactory manner the experimental data, like the period doubling route to chaos in the KDP crystal near the ferroelectric transition temperature [6]. Later, the same material has been found to present a different route to chaos, named the period doubling of torus, which has been numerically investigated by Kaneko [8-9] in high dimensional systems ($d \geq 3$ for maps or $d \geq 4$ for continuous flows). This scenario of transition to chaos represents a mixture between the period doubling scenario and the quasiperiodicity one. In the paper of Shin [7] there were identified two anharmonic oscillators coupled electromechanically, each of which is a representative example of a dynamical systems showing period doubling and quasiperiodicity.

In the present paper we present preliminary results on nonlinear behaviour of a Metal-Ferroelectric-Semiconductor structure consisting of a thin $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ polycrystalline ferroelectric

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film. This is, to our knowledge, the first investigation on nonlinear dynamics performed on a MFS structure of this type. We focus only on a period-doubling bifurcation evolution to chaos induced by the change in the amplitude of a sinusoidal driving.

2. Experimental set-up

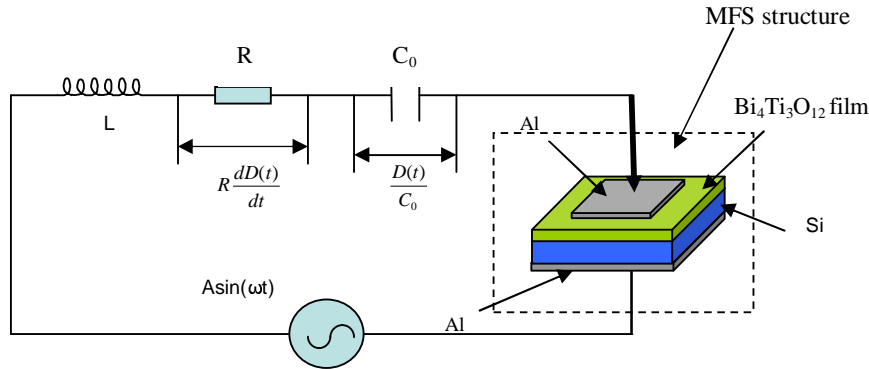


Fig. 1 Experimental set-up.

The experimental set-up consists on an RLC series circuit with the MFS structure acting as a nonlinear capacitance, in series with a linear capacitance C_0 , a resistance R and an inductance L (Fig. 1). The MFS structure was fabricated by sol-gel deposition of a $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ (BIT) film on a p-type Si(100) substrate with a resistivity of 1-10 Ωcm . The thickness (286 ± 15 nm) of the BIT film has been determined by scanning electron microscopy (SEM). X-Ray-Diffraction (XRD) analysis showed a polycrystalline structure for the ferroelectric layer. The electrical contacts have been realised by vacuum evaporation of Al. The top contact (on the BIT material) was profiled using a mask, while on the back (on the Si substrate), Al was evaporated on the entire surface. Between the Si and BiTiO, a layer of 6 nm silica oxide (not shown in Fig. 1) is interposed. Finally, the structure was thermally treated in air at 650 $^\circ\text{C}$ for 30 minutes.

The RLC series circuit is externally driven by a harmonic voltage generator (HP8116A). The voltage drop on the resistance (proportional to the derivative of the dielectric displacement D) and the voltage drop on the linear capacitor (proportional to D) have been simultaneously monitored by an oscilloscope (TDS 540A) and subsequently acquired on a PC.

3. The theoretical model

The MFS structure presents a high asymmetry in its electrical response. When a positive voltage is applied to the metal, the extrinsic substrate (here p-type Si) is driven into deep depletion. If the frequencies of the signal are too high for the minority carriers (electrons) to respond to the signal, the inversion layer at the Si surface could not build up. As a consequence, the voltage drop on the MFS structure is large due to the relatively large width of the depletion layer in the Si. When a negative voltage is applied to the metal, the substrate is driven into a strong accumulation and the voltage drop on the Si is low. It results that for the same amplitude, the distribution of the voltages on MFS structure and the linear elements in the circuit is different for negative and positive driven signal. We can model this behaviour as an intrinsic nonlinear oscillator of Duffing type.

As extensively demonstrated, coupled nonlinear oscillators can model a large class of complex dynamics observed in different physical systems [7,10-11]. We propose a model system of two coupled nonlinear oscillators of Duffing type. One is modelling the RLC circuit with the MFS structure as nonlinear capacitor and as the other one, the intrinsic oscillator described above. The system of equations is:

$$\begin{aligned} x''(t) - a_1 x(t)[1 - mx^2(t)] + b_1 x'(t) - d_1 y(t) &= c_1 \sin(\omega t) \\ y''(t) - a_2 y(t)[1 - ny^2(t)] + b_2 y'(t) - d_2 x(t) &= c_2 \sin(\omega t - \varphi_0) \end{aligned} \quad (1)$$

For the simulation shown in Fig. 2 and 3 the values of the parameters are: $a_1 = 1$; $a_2 = 0.5$; $b_1 = 0.2$; $b_2 = 0.1$; $m = 3.1$; $n = 1$; $c_1 = c_2 = c$ (as shown on each graph) and $\varphi_0 = 0$. We consider symmetrical coupling with strength described by $d_1 = d_2 = 0.1$.

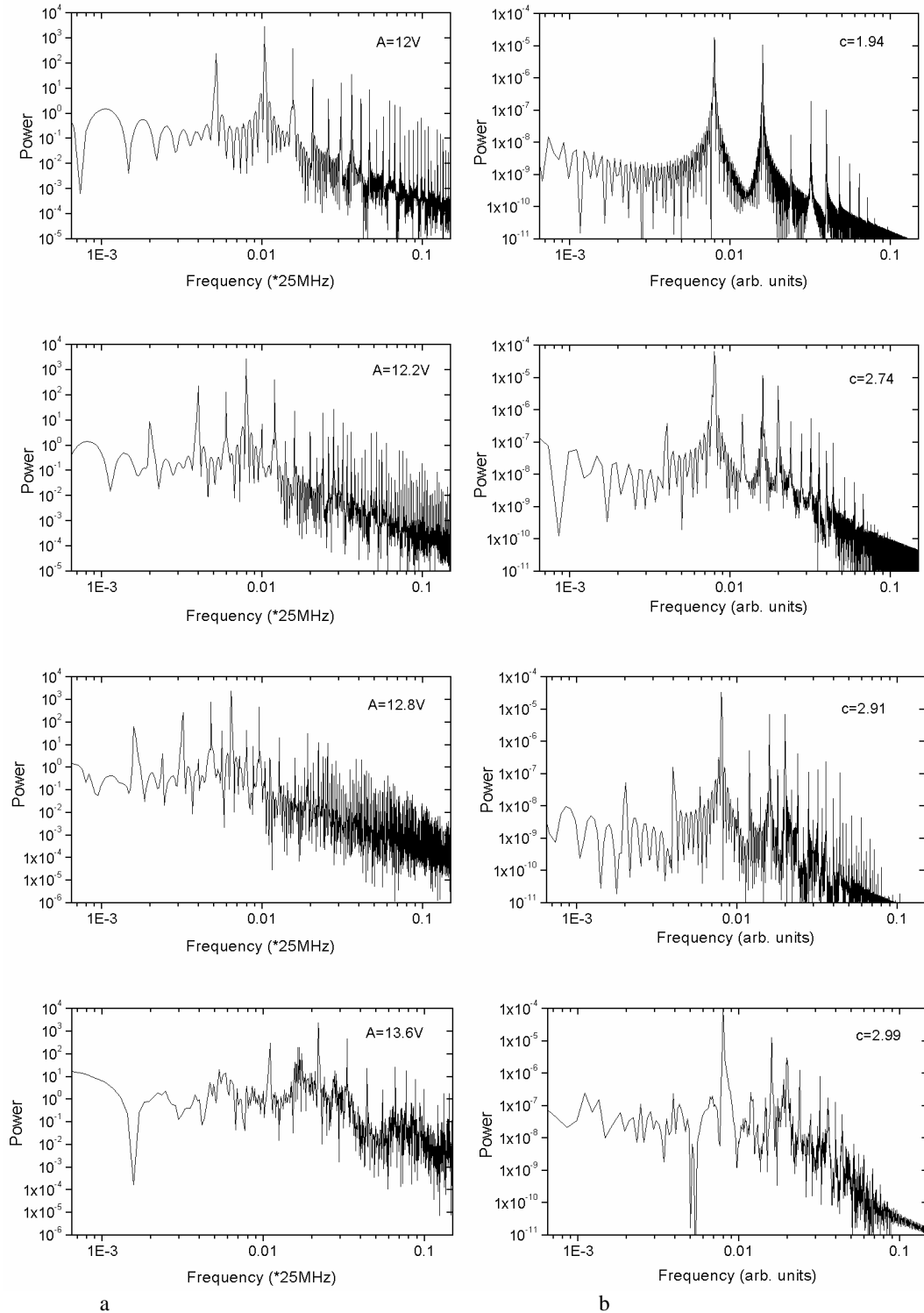


Fig. 2. FFT spectra: experimental (a) and the corresponding theoretical ones (b). The value of the amplitude of the driving voltage (A) and the corresponding control parameter (c) is shown on each graph.

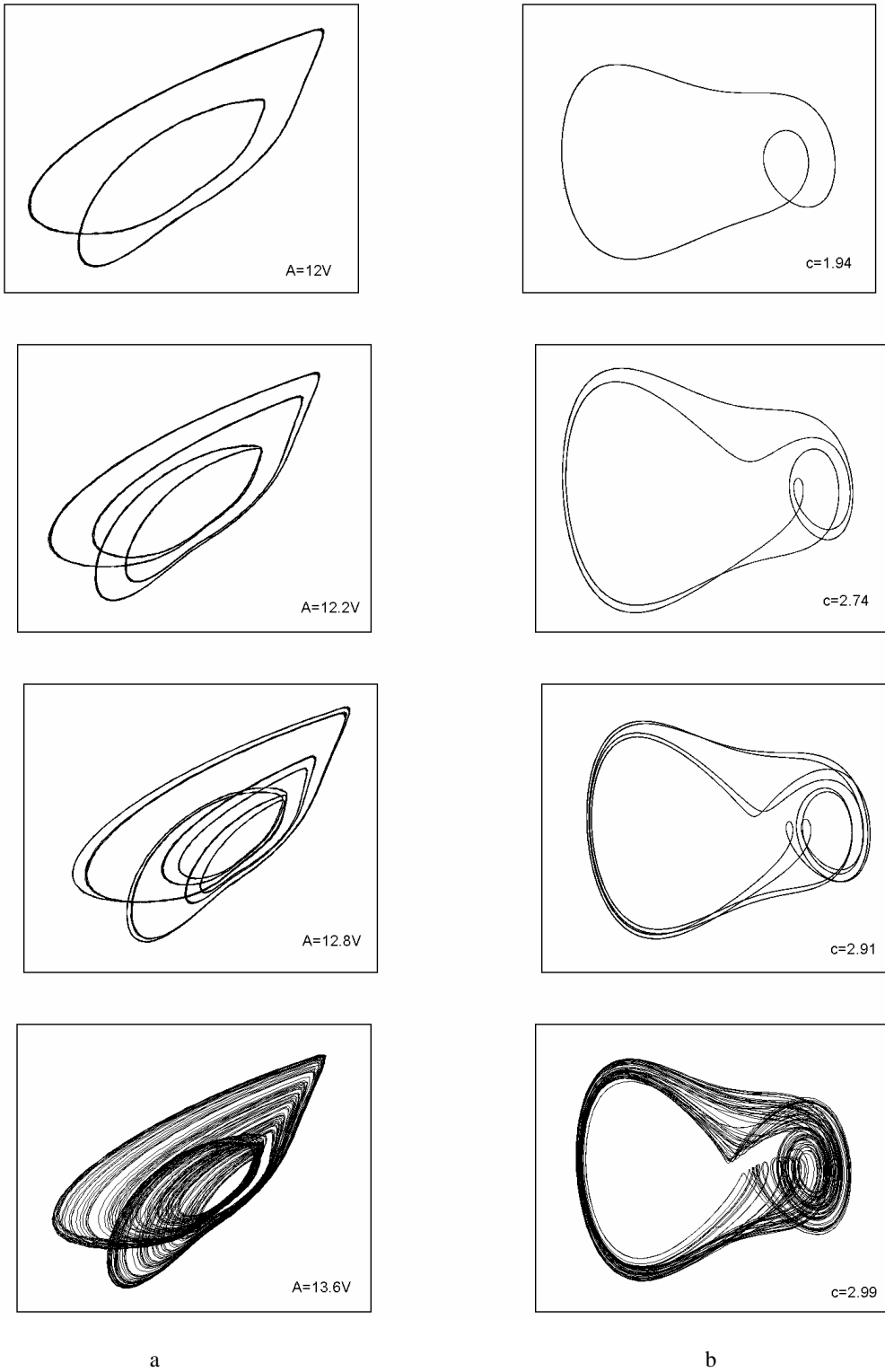


Fig. 3. Phase space projections: experimental (a) and the corresponding theoretical ones (b) side. The value of the amplitude of the driving voltage (A) and the corresponding control parameter (c) is shown on each graph.

4. Results and conclusions

The experimental results presented in the left column in Fig. 2 and Fig. 3 represent one of a large number of a bifurcation sequences observed in the dynamics of the system caused by the change in the amplitude of the driving voltage. With increasing of the amplitude, transitions from period 2 to period 4 and then to period 8 and finally to chaos is shown from top to bottom. The right hand side column shows the same sequence of transitions as obtained from computation based on the system of equations corresponding to the coupled Duffing oscillators.

The results in Fig. 3 show that the theoretical model considered can only simulate the main topology of the phase space and future improvement is necessary to obtain detailed reproduction of the phase portraits [4]. Our research on this problem is in progress and other observed types of dynamics such as cascade of doubling of torus and evolution to chaos by Ruelle-Takens-Newhouse scenario will be presented in a future, more extended paper.

The investigation on nonlinear dynamics performed on this type of MFS structure and a correct modelling can represent a new way for understanding the microscopic processes involved.

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