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Detection of hidden structures in a photoexcited semiconductor via principal-component analysis

Yuo-Hsien Shiau *

Department of Physics, National Dong Hwa University, 1, Sec 2, Da-Hsueh Road, Shou-Feng, Hualien 974, Taiwan, ROC

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Abstract

We study the transport properties of a GaAs-based semiconductor under local optical excitation via direct numerical simulation. The simulation results propose a hypothesis which describes the possibility to control the high-field domain in terms of tunable modulations of the doping profile and the length of the notch region. This hypothesis can be verified, both quantitative and qualitative agreement, via principal-component analysis. Besides, higher harmonic modes embedded in the high-field domain also can be automatically extracted from principal-component analysis. This study might be useful to identify the "effective" length and shape of the cathode notch and to restore the doping concentration in semiconductor devices.

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1. Introduction

Recently, the operating frequency of Gunn diodes at their harmonic modes rather than their fundamental modes have became a major issue for the development of new microwave devices [1,2]. A number of researchers addressed that the higher harmonic efficiency is dependent of various doping profiles [3–6]. And the related doping profiles including uniform doping, graded doping, and notch doping are also studied in detail [5]. The fundamental reason for the study of the doping profile is the waveform of current oscillations and the associated higher harmonic modes are strongly related with the characteristics of the domain formation process and the dynamics of its propagation through the active region, and which are determined by the doping profile. However, the doping profile is reliant on the mature semiconductor technologies, but the output profile and/or the dynamical response, sometimes, are not expected for the producer. The reasons for these unexpected results can be from two possible sources. One of them is that the present technology is not stable for device fabrication. The other is the transport properties of the device can be influenced from the environment or the artifacts. Therefore, an efficient method for detection of the doping profile is quite important in the semiconductor industry.

The restoration of the spatial structure of heterogeneous materials from two-point correlation functions is an inverse problem of fundamental importance [7,8]. Many experimental techniques are used for the characterization of heterogeneous media, for example, small-angle X-ray and neutron scattering etc. In this study, we want to use the principal-component analysis (PCA), i.e., a statistical method, to detect the spatial characteristics in a GaAs-based n^+–n^-–n–n^+ semiconductor via analyzing the

* Tel.: +886 38633718; fax: +886 38633690.
E-mail address: yhshiau@mail.ndhu.edu.tw

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domain dynamics. These characteristics are, both quantitative and qualitative identification, resulted from the external dc bias and the original doping profile (ODP). Furthermore, higher harmonic modes embedded in the high-field domain also can be automatically generated via PCA. In order to illustrate the power of PCA more clearly, the case of local optical excitation near to the cathode notch (i.e., n^- region) is also considered. The motivation of considering local optical excitation in the active region (i.e., n and n^- regions) is to redistribute the space-charge field around the doping notch via optical generation of hole carriers. More precisely speaking, local optical excitation is to make this doping notch as a collector of electrons. Then, the internal field in the doping notch will become stronger, which can speed up the electrons and influences the dipole-domain nucleation. Therefore, if the optical intensity is large enough, even at a lower dc bias, the quenched domain possibly becomes the transit domain. Thus the so-called optical control of electrical propagations in a GaAs-based Gunn device is expected. Although this idea can be easily verified in terms of numerical calculations [9]. However, the underlying physics shall be relative to the domain dynamics under the consideration of various doping profiles. The problem is that we just consider one kind of doping profiles, and which can exhibit different dynamical characteristics even at a fixed and lower dc bias. Fortunately, based on the language of PCA, this kind of transition from the quenched to transit domains is corresponding to the change of "effective" doping profiles (EDPs), which are determined by the external dc bias, the optical excitation, and the ODP. Therefore, EDPs can be regarded as hidden structures in semiconductor devices under various operation conditions. Moreover, in order to detect EDPs in real situations, the photorefractive effect [10] we propose to identify these hidden structures.

It is also deserved to note that the physical phenomena due to the interaction between laser light and semiconductor active devices have received a great deal of attention because of their immediate applications in modern telecommunications systems. A large number of researchers have reported detailed investigations of optically controlled active devices over the last 20 years [11]. The present PCA analysis we believe could be generally applied to the so-called illuminated devices and provides a different point of view in transport dynamics.

The remainder of this paper is organized as follows. In Section 2, we describe the details of our drift-diffusion model which is well accepted in semiconductors. The concept and the related statistical meanings in PCA are given in Section 3. Section 4 contains the central part of our paper including numerical results and discussions. Section 5 is our concluding remarks.

2. The transport model

As the sandwich structure we consider a GaAs-based Gunn device with the doping profile $N_D(x)$ (i.e., ODP), denoted as n^+ (8.0 μm)–n^- (4.0 μm)–n (40.0 μm)–n^+ (8.0 μm), shown in Fig. 1. The active region is sandwiched between the highly-doped n^+ cathode and anode regions. A 4 μm doping notch, at the beginning of the active region of the Gunn device, is to initiate the dipole domain near the cathode. In addition, the laser illumination with 3 μm width is considered and denoted as $I(x)$ [12]. The detailed model equations and GaAs parameters in our simulation are listed in Tables 1 and 2. In the following, the results obtained from direct numerical simulation (DNS) with the consideration of the drift-diffusion model and fixed boundary conditions will be demonstrated in detail.

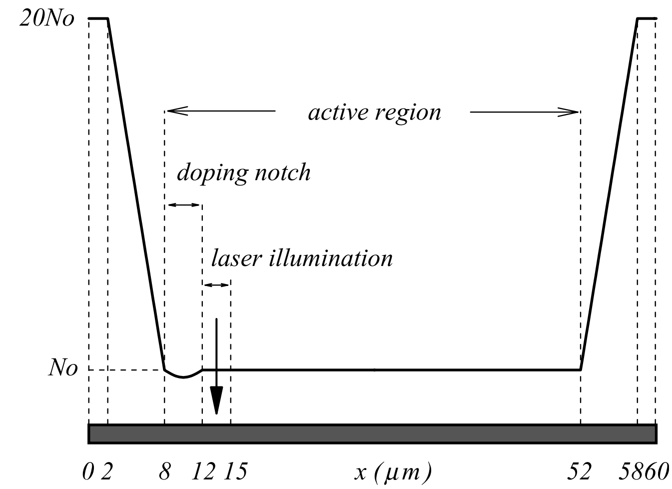

Fig. 1. Schematic illustration of the device doping profile $N_D(x)$ and the local laser illumination $I(x)$.

3. Principal-component analysis, PCA

In order to realize the mutual information and the nonlinear coupling between the different locations in this semiconductor, the cross-correlation method is used and defined as the following matrix form [13,14]:

$$C_{ij}(T) \equiv \frac{\langle (E_i(t) - \langle E_i \rangle)(E_j(t) - \langle E_j \rangle) \rangle_T}{\sigma_i(T)\sigma_j(T)}, \tag{1}$$

where $E_i(t)$ and $\langle E_i \rangle$ denote, respectively, the electric field measured at the ith location and the average values of $E_i(t)$ during the recorded time interval T. The symbol $\langle\ \rangle_T$ also represents an average values for $(E_i(t) - \langle E_i \rangle)(E_j(t) - \langle E_j \rangle)$ in time interval T. $\sigma_i(T)$ is the standard deviation of $E_i(t)$ and $C_{ij}(T)$ is the matrix element contributed by the ith and the jth locations in the semiconductor. According to the definition of Eq. (1), we can construct the symmetrical correlation matrix C and numerically find the eigenvalues ξ_n.

$$C|\xi_n\rangle = \xi_n|\xi_n\rangle, \tag{2}$$

where $|\xi_n\rangle$ being the corresponding eigenvectors. n is a positive integer which shall be smaller than or equal to the number of locations we consider. Then, the eigenvalues