Solid-State Electronics 56 (2011) 60–67

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Physical limitations of the diffusive approximation in semiconductor device modeling

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ARTICLE INFO

Article history:
Received 19 April 2010
Received in revised form 26 August 2010
Accepted 1 November 2010
Available online 26 November 2010

The review of this paper was arranged by Prof. S. Cristoloveanu

Keywords:
Transport phenomena
Forward biased bipolar structures
High current density

ABSTRACT

Criteria for occurrence of the quasineutral diffusion mode have been investigated in terms of a generalized approach that takes into account the dependences of the electron and hole velocities on the electric field. These criteria should be used to describe the carrier transport in bases of forward biased bipolar semiconductor devices (diodes, thyristors, and power bipolar transistors in the saturation mode). The criteria appreciably differ from the previously obtained commonly accepted criteria. It is demonstrated that equations describing the carrier transport in the quasineutral approximation in *n*- and *p*-type semiconductors are different. These equations are used to obtain analytical conditions in which the diffusion mode is operative. The applicability limits of the diffusion approximation in simulation of semiconductor structures are found. The analytical results are confirmed by a numerical experiment.

1. Introduction

Theoretical foundations of operation of bipolar semiconductor devices (diodes, thyristors, and bipolar transistors in saturation modes) were formulated and developed in the early 1960s. Hundreds of original papers, tens of reviews, and numerous monographs have been devoted to analysis of various operation modes. The most exhausting description of the results obtained can be found in the classical book [1]. All the necessary references can also be found in Ref. [1].

One of the main objectives currently being pursued in modern semiconductor electronics is the development and application of wide-bandgap semiconductor materials: silicon carbide (SiC) and Group-III nitrides. Thanks to the excellent electrical and physical properties of SiC, these devices can operate at pulse current densities of up to 10^5 A/cm^2 [2,3]. The current densities in bipolar devices based on direct-gap GaN may be even larger than those in SiC-based devices, because of the re-absorption of radiative recombination [4]. Modern growth technologies of SiC and GaN epitaxial films can yield high-quality layers of these materials with thicknesses of several hundred micrometers and create on the basis of these layers very high-voltage semiconductor devices. For example, SiC rectifier diodes with a breakdown voltage of about 20 kV have been demonstrated. The base width in these structures is about 200 μm [5]. At the same time, non-equilibrium carrier lifetimes τ in SiC and, especially, GaN are comparatively short despite the very rapid progress in this field. For example, the maximum value of τ, reported for SiC epitaxial films at room temperature, is 3.7 μs [6]. At $W = 200$ μm, this lifetime corresponds to $W/L \approx 4.6$ (here W is the base width and L is the ambipolar diffusion length). For GaN-based devices, for which the achieved values of τ are appreciably smaller, the W/L ratios in model high-voltage structures may be even larger. The cases of large W/L ratio can be realized in high-frequency Si devices as well. For example, the lifetime in so called "modulator thyristors" is suppressed to achieve the maximum rate of switch-on. The lifetime on Si devices is reduced under effect of gamma, proton, and fast electron irradiation.

As mentioned in Refs. [2,7], some specific features of steady-state and transient device characteristics, observed under these conditions, are difficult to explain in terms of the conventional approach [1].

In particular, in Ref. [2] non-monotonic dependence of differential resistance R_d of forward biased SiC rectifier diode on current density has been observed at very high injection level. At current density $j \approx 5000$ A/cm^2, a very sharp *decrease* in differential resistance has been obtained with further j increase. At $j \geqslant 4 \times 10^4$ A/cm^2, the differential resistance *increases* with further growth of j. A dependence of this type cannot be obtained in terms of any known analytical model. In any conventional approach, the differential resistivity of a forward-biased diode at high injection levels always decreases monotonically and tends to a constant value

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0038-1101/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2010.11.001

("saturates") at very high j. However, simulation in the frame of adequate numerical model not only confirms the possibility of experimentally observed phenomena, but predicts possibility of negative differential resistance (NDR) at high current density (see Fig. 1 in Ref. [7]). Meantime, it is well known that unique interpretation and analysis of solutions to a non-linear equation is difficult (and, in many cases, impossible) without an adequate analytical consideration. In addition, despite the very wide use of simulations for analysis of operation of semiconductor devices, a numerical solution of two-dimensional (2D) and, especially, 3D equations requires such a large computational burden that analytical estimates frequently become the only possible practical way to tackle with the problem. That's why we revised a classical approach in effort to understand the physical nature of non-classical phenomena observed experimentally and predicted in the frame of adequate simulation.

In Ref. [8] it was shown that, along with the well-known *quasineutral diffusion* and *quasineutral drift modes* [1], a new Diffusion Stimulated by Quasineutral Drift (DSQD) mode can be put into effect in bipolar semiconductor structures under a forward bias. In addition, it was demonstrated in Ref. [7], that the equation describing the carrier distribution in the quasineutral approximation should be changed by taking into account the field dependence of the mobility. Analytical approach developed in Refs. [7,8] makes it possible to explain qualitatively the nature of non-monotonic differential resistance and NDC in forward biased bipolar structures.

However, two very important points were not clarified in Refs. [7,8]. First, appropriate equations taking into account field dependence of the mobility were obtained in Ref. [7] only for structures with n-base. Meantime, unlike "classical" model, the equations describing the carrier distribution under a forward bias for structures with n- and p-bases are different in the case under consideration. Second, the diffusion, drift, and DSQD modes contribute differently to the forward drop across the base layers of semiconductor devices (and, consequently, to the energy loss). Just the *quasineutral diffusion mode* provides minimum forward drop across the base layers of semiconductor structures. That is why, a considerable time has been devoted to consideration of quasineutral diffusion approximation criteria [1,9]. However, criteria for occurrence of the diffusion mode were not specified in Refs. [7,8].

In the present study, we formulate criteria for occurrence of the quasineutral diffusion mode in terms of the generalized approach developed in Refs. [7,8] for structures with n- and a p-bases.

2. Basic equations for the carrier distribution in the quasineutral approximation for forward biased structures

Let us consider a carrier distribution along the p^+–i–n^+ structure (here symbol "i" signifies low-doped base of p- or n-type). As it was shown in Refs. [7,8], in general case, three different quasineutral modes of carrier distribution are operative in different parts of the base: diffusion, drift, and DSQD modes. Schematic carrier distribution for a p^+–n–n^+ structure considered in details in Ref. [7] is shown in Fig. 1.

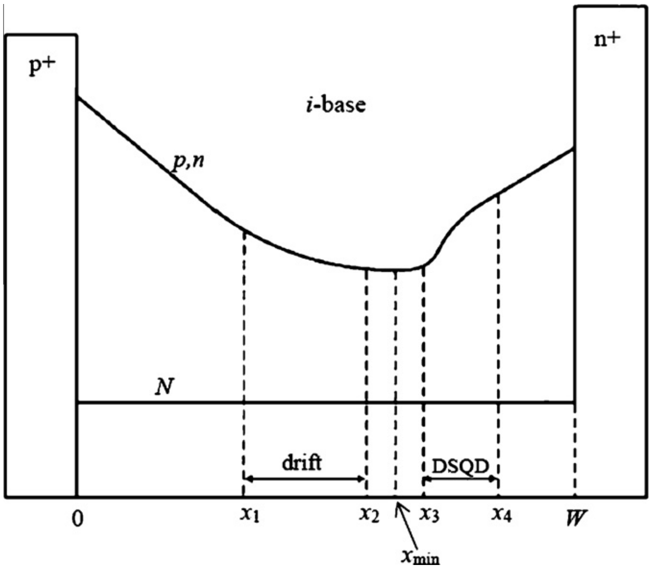

Fig. 1. Schematic of a carrier distribution along p^+–n–n^+ structure. In the regions 0–x_1, x_2–$x_{\min}$, $x_{\min}$–x_3, and x_4–W, quasineutral diffusion mode is realized. In the region x_1–x_2, the drift mode is realized. In the region x_3–x_4, the mode of diffusion stimulated by quasineutral drift (DSQD) is operative. N is doping level of the base.

However, the possibility of different modes realization depends on the current density and parameters of the structure. We are going to formulate here criteria of the situation, when just quasineutral diffusion mode is realized along whole base layer (0 < W). As mentioned above, this situation corresponds to minimum possible forward drop across the base layer of semiconductor structure (and, consequently, to minimum of the energy loss).

The equation for electron current under high injection level ($n \approx p \gg N_d$) in a structure with base of n-type was obtained in Ref. [7]:

$$j_n = \frac{jb}{b+1} + \frac{jb}{(b+1)^2}\left(\frac{N_d}{n}\right) - \frac{jb}{(b+1)^2}\left(\frac{F}{F_{ns}} - \frac{F}{F_{ps}}\right) + q\frac{2b}{b+1}D_{p0}\frac{dn}{dx}, \tag{1}$$

where q is an elementary charge, j is the total current, $b = \mu_{n0}/\mu_{p0}$, μ_{n0} and μ_{p0} are the low-field mobilities for electrons and holes, respectively, p is hole concentration, $F = \frac{j}{q(\mu_{n0}+\mu_{p0})p}$ and $D_{p0} = \frac{kT}{q}\mu_{p0}$; N_d is a donor concentration. Definitions for F_{ns} and F_{ps} are given in Appendix A

Similar equation for electron current in a structure with base of p-type has been obtained in Appendix A:

$$j_n = \frac{jb}{b+1} - \frac{jb}{(b+1)^2}\left(\frac{N_a}{n}\right) - \frac{jb}{(b+1)^2}\left(\frac{F}{F_{ns}} - \frac{F}{F_{ps}}\right) + q\frac{2b}{b+1}D_{p0}\frac{dn}{dx} \tag{1$'$}$$

here N_a is an acceptor concentration.

Eqs. (1) and (1′) differ in the sign of the second term on their right-hand sides. This situation can be understood by taking into account that the second terms in Eqs. (1) and (1′) are directly proportional to the difference between the electron and hole concentrations (which is always small at high injection levels). In the p-type base layer, the concentration of holes exceeds that of electrons. In the n-type base layers, we have the opposite situation. That is why the second terms in Eqs. (1) and (1′) have different signs.

The third terms in Eqs. (1) and (1′) are related to the field dependence of the mobility. In almost all of the known semiconductors (Ge, Si, GaAs, SiC, GaN, etc.) $F_{ns} < F_{ps}$. With the fact taken into account, it is clear that a small decrease in mobility with increasing field results in that appropriate terms of the same sign appear in Eqs. (1) and (1′). It is noteworthy that the sign of these terms is independent of whether carriers (holes/electrons) are minor or major carriers in the situation in question. The corresponding term for electrons is always negative, and that for holes, always positive.

Substituting (1′) into the continuity equation for electrons:

$$\frac{1}{q}\frac{dj_n}{dx} = \frac{n}{\tau}, \tag{2}$$

where τ is the carrier lifetime at a high injection level, we obtain, after standard transformations, an equation that describes in the