A model for the dc electrical behavior of bulk-barrier diodes

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Contents This paper presents an analytical model for the dc electrical behavior of bulk barrier diodes (BBD’s). The proposed model extends previously published models, and includes analytical expressions for all significant quantities of the device dc performance, i.e. barrier height, current density and ideality factor, with respect to the technological parameters and the applied voltage in both bias conditions. The analytical results have been compared with those obtained using the 2-D device simulator S-PISCES, which takes into account the drift–diffusion theory, as well as a concentration and field dependent mobility, the Shockley–Read–Hall and Auger carrier recombination, and the band gap narrowing. Good agreement was obtained between theory and simulation. The device simulation played a very important role in best understanding BBD’s behavior, because it could easily take into account parameters strongly affecting the behavior of BBD’s, e.g. the free carrier presence in depletion layers, which was very difficult for the analytical model to include.

Key words Bulk-barrier diodes, majority carrier devices, electrical behavior

1 Introduction

Bulk-barrier diodes (BBD’s) [1, 2], or camel diodes (CD’s) [3, 4], are two-terminal three-layer structures similar to bipolar junction transistor (BJT), where the current is controlled by a potential barrier located inside the semiconductor. However, contrary to the BJT’s, the middle (base) region in BBD’s is so thin that it is normally fully depleted from free carriers, and there exists no neutral region. Similar structures appear in the literature with different names: “bulk unipolar diodes” [5–7], “triangular barrier diodes” [8], and “P-plane diodes” [7]. All the above structures are, like Schottky diodes, majority carrier devices and, therefore, they can be used for high-speed applications. Contrary to the Schottky diodes, BBD’s offer the possibility to control the barrier height by well controllable technological parameters, such as dopant concentration and middle layer width. This advantage over the classical Schottky diode makes them very attractive in many applications. There are several published works referring to the applications of such structures as photodiodes with high internal gain [4], high speed optoelectronic switches [9, 10], temperature sensors [11], bulk-barrier transistors [12, 13], gates in FET’s [14], and as microwave devices [15]. Details for the fabrication and the electrical performance of such structures were firstly reported by Mader [2] and Shannon [3]. They introduced approximate equations for the description of the barrier height and the current density. Calculations of the electrical properties of such structures were also presented by Al-Bustani [7, 8].

So far, no analytical model has been presented, that could describe the barrier height, ideality factor and the current densities in both bias conditions. Furthermore, the performance of these structures has not been investigated by proper consideration of the limitations posed by technological parameters (dopant concentration, middle layer thickness) as well as by the free carrier effect. In order to facilitate the applications of BBD’s, we propose a detailed analytical model for their operation. The proposed model describes the quantities: potential barrier (Φ), ideality factor (η), and current (I) in both bias conditions (Sect. 2). The validation limits of the above quantities are investigated taking into account the technological parameters. Process and device simulation programs were also used for the validation of the above analytical model, i.e. S-SU- PREM4 and S-PISCES, respectively, as well as for further elucidation of the effect of various parameters, such as the free carrier presence in space-charge regions, strongly affecting the behavior of BBD’s.

2 Theoretical analysis

2.1 Thermal equilibrium

Figure 1 shows the structure of the BBD, and the distribution of space charge density, ρ(x), electric field, E(x), and electrostatic potential, V(x), under equilibrium (—) as well as under forward (-----) and reverse (------) bias conditions (------). Total depletion of the n layer, achieved by proper choice of the thickness and doping concentration of the middle layer, is a prerequisite for BBD operation. If the contribution of free carriers to the total charge is neglected, charge neutrality requires that the positive space charge in the n region should be equal to the sum of the
negative space charges in both the p⁺ and p regions. It is also assumed that the three layers are uniformly doped with concentrations: \(N_C\) in the substrate layer (collector), \(N_B\) in the middle layer (base), and \(N_E\) in the surface layer (emitter). The solution of Poisson’s equation, in thermal equilibrium, leads to a potential barrier height, \(\Phi_{BL0}\), given by:

\[
\Phi_{BL0} = \frac{q \cdot N_E \cdot x_{EB}^2}{2 \varepsilon} + \frac{q \cdot N_B \cdot x_{C0}^2}{2 \varepsilon} - \frac{q \cdot N_B}{2 \varepsilon} \left[ \frac{N_B}{N_E} \left( d - x_{C0} \frac{N_C}{N_B} \right) \right]^2 + \frac{q \cdot N_B}{2 \varepsilon} \left[ d - x_{C0} \frac{N_C}{N_B} \right]^2
\]

or

\[
\Phi_{BL0} = V_B \left( 1 + \frac{N_B}{N_E} \right) \left( 1 + \frac{N_C}{N_B} \right) \frac{N_C}{N_B} \left( 1 + \frac{N_B}{N_E} \right) - V_D - 2 \cdot V_B \left( 1 + \frac{N_B}{N_E} \right) \sqrt{\frac{N_C}{N_B + N_C} \left( 1 - \frac{V_D}{V_B} \right)}
\]

with

\[
V_B = q \cdot N_B \cdot d^2 / 2 \cdot \varepsilon
\]

where, \(x_{EB}\) and \(x_{C0}\) are the depletion region widths in the emitter and collector layers, respectively, \(x_0\) is the point where the electric field is zero, \(d\) is the middle layer thickness, \(q\) is the electron charge, \(\varepsilon = \varepsilon_0 \varepsilon_r\) is the dielectric constant, and \(V_D\) is the difference between the Fermi-level potentials in the p⁺ and p layers, and it is given by:

\[
V_D = V_T \cdot \ln \left( \frac{N_E}{N_C} \right)
\]

where \(V_T = kT/q\). For \(N_E \gg N_B \gg N_C\), Eq. (2) takes the following form [2]:

\[
\Phi_{BL0} \approx V_B \approx q \cdot N_B \cdot d^2 / 2 \cdot \varepsilon
\]

The values of \(\Phi_{BL0}\) obtained using Eqs. (2) and (5) differ by about 5% when \(N_C/N_B = 10^{-3}\), whereas this difference reaches the value of 44% when \(N_C/N_B = 10^{-1}\). This could lead to current differences greater than five orders of magnitude (10⁵).

For given \(N_E\), \(N_B\) and \(N_C\), there is a lower limit for \(d\), below which the BBD becomes a p⁺-p junction. There also exists an upper limit for \(d\), above which a neutral region appears in the n layer, and the BBD tends to behave as a bipolar junction transistor. Consequently for BBD operation it must be:

\[
V_D/\Phi_{BL0} (V_{DEB})
\]

where \(V_{DEB}\) is the build-in potential of the p⁺-n junction and \(n_1\) is the intrinsic carrier concentration. Substituting Eqs. (4), (5) and (7) into Eq. (6), we can calculate the limits of \(d\):

\[
d_{min} = \left( L_D \cdot \sqrt{\frac{N_E}{N_C}} \right)
\]

\[
< d < d_{max} = \left( L_D \cdot \sqrt{2 \ln \frac{N_E}{N_B} / n_1^2} \right)
\]

where \(L_D\) is the Debye length in the n type region given by:

\[
L_D = \sqrt{\varepsilon \cdot V_T / q \cdot N_B}
\]

It is evident from all the above, that the potential barrier height, \(\Phi_{BL0}\), is mainly a function of technological parameters \(N_E\), \(N_B\), \(N_C\), and \(d\). For given \(N_E\) and \(N_C\), the limits of BBD operation can be controlled by the values of the middle layer thickness \(d\) and \(N_B\).

2.2 Operation under bias conditions

Figure 1d shows qualitatively the variation of the potential barrier under bias conditions. For reverse bias (i.e. + on the emitter and — on the collector), the depletion layer width within the substrate expands, and the potential barrier height on the right side of the middle layer, \(\Phi_{BR}\), increases. At the same time the potential barrier on the left side, \(\Phi_{BL}\), decreases, and so in this case the hole current over this barrier dominates. The opposite is valid for forward bias, where the hole current over the barrier \(\Phi_{BR}\) dominates. Equation (2) for \(\Phi_{BL}\) under bias conditions takes the form: