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A Single Junction Barrier Model for Varistors

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Abstract

In this paper, we propose a simplified model that explains the experimental behaviour of the single junction barrier height in varistors. The equation obtained for the barrier height variation versus voltage contains all parameters that characterize the grain boundary and has no adjustable parameters. It allows us to describe the equilibrium state for each voltage level. From this model, it is concluded that the threshold voltage and the nonlinearity coefficient for a single junction barrier are strongly related to the unoccupied traps level at zero bias, when the barrier height at zero bias and the leakage current are related to the filling traps level.

Key Words: Varistors, ZnO, Grain boundary, Barrier height.

1. Introduction

Metal-oxide varistors are ZnO-based ceramics devices with highly nonlinear current-voltage characteristics. The intergranular regions of this polycrystalline solid have a significant effect on the conduction mechanism. The grain boundaries contain defects which often trap majority carriers and it is widely accepted that trapping electrons at the interband states of grain boundaries form the double schottky barrier. However, no model has succeeded in consistently explaining experimental data reported so far. Generally, based on the model suggested by Levine [1], the theoretical models published [2–5] are limited by some assumptions, namely those concerning the density of grain-boundary traps states. The threshold voltage obtained is constant and directly related to the band gap of ZnO, contrary to some experimental results. It is the purpose of this paper to show that, by making some modifications, with the major difference being the inclusion of two types of electrons traps level, it is possible to overcome the earlier objection. The theoretical behaviour of the barrier height versus applied voltage is determined for one grain boundary with some assumptions concerning the variation of the occupancy of these traps state under polarization. Next, we examine the influence of all parameters that characterize the grain boundary on the barrier height.

2. Model

Barrier height ϕ versus applied voltage V is determined via calculation of positive charge Q_+ and negative surface charge Q_S. Then we write the charge conservation law that Q_+ and Q_S must respect. Taking into account the all types of carriers in the case of non degenerate statistics, we get the same equation obtained

by Dorlanne [3] for the positive space charge Q_+:

$$Q_+ = (\varepsilon_r\,\varepsilon_0\,N_d\;K_BT)^{1/2}\left[\begin{array}{l}\left\{-\frac{\varphi}{K_BT}+\;\exp\left(-\frac{\varphi}{K_BT}\right)+\exp\left(-\frac{(q\,V_g\,-\varphi)}{K_BT}\right)\;-1\right\}^{1/2}\\ +\left\{\frac{\varphi+qV}{K_BT}+\exp\left(-\frac{\varphi+qV}{K_BT}\right)+\exp\left(-\;\frac{qV_g-\varphi-qV}{K_BT}\right)\;-\;1\right\}^{1/2}\end{array}\right], \tag{1}$$

where ε_r is the dielectric constant of ZnO, N_d the donor density, K_B the Boltzmann constant, T the temperature and V_g the gap of the semiconductor grain. We remark that if the minority carriers are neglected, equation (1) is the same one obtained by Pike [2].

To calculate the negative surface charge, we propose the existence of two types of traps states, N_{S1} and N_{S2}, at different energetic levels E_1(with bandwidth ΔE_1) and E_2(with bandwidth ΔE_2). One is close to the conduction band E_c while the other situated between the valence band E_v and the intrinsic Fermi level. Under these conditions, and if we consider a uniform distribution for both types, Q_S is given by the relation

$$Q_S = Q_{S1} + Q_{S2} = -q(N_{S1}\Delta E_1 + N_{S2}\Delta E_2), \tag{2}$$

where N_{S1} and $N_{S2}$are in units of $\mathrm{Cm}^{-2}/\mathrm{eV}$.

Our second hypothesis concerns the occupancy of these two levels according to the bias voltage. We suppose that, at zero bias, only the E_1 state traps electrons, when the E_2 state is empty. Under polarization, the density of E_1 level begin to decreases and if the voltage exceeds E_2/q , the empty state level E_2 begin to fill progressively. These trapped electrons are emitted toward the conduction band when the applied voltage exceeds $(E_c - E_2)/q$. It is assumed that traps at all energies exchange electron only with the band conduction state, and not among themselves. If the densities of the trap states at zero bias are respectively N_{S10} (filled) and N_{S20} (empty), we can write:

$$N_{S1} = N_{S10}f_1(v) \text{ and } N_{S2} = N_{S20}f_2(v), \tag{3}$$

where $\mathrm{f}_1(v)$ and $\mathrm{f}_2(v)$ represents the occupancy variation respectively for $E_1$and E_2. Schematically, these variations are showed on Figure 1.

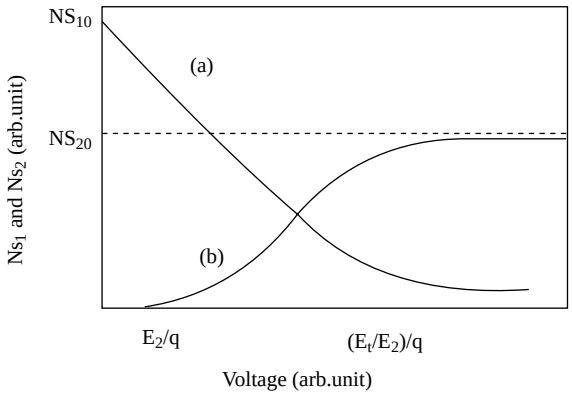

Figure 1. Illustrative forms for the occupancy versus voltage for (a) the state level E_1, (b) the state level E_2.

Finally, we write the charge conservation law that Q_+ and Q_S must respect. We obtain:

$$\left[\begin{array}{l} \left\{ -\frac{\varphi}{K_B T} + \exp\left(-\frac{\varphi}{K_B T}\right) + \exp\left(-\frac{(q\,V_g - \varphi)}{K_B T}\right) - 1 \right\}^{1/2} \\ + \left\{ \frac{\varphi + qV}{K_B T} + \exp\left(-\frac{\varphi + qV}{K_B T}\right) + \exp\left(-\frac{qV_g - \varphi - qV}{K_B T}\right) - 1 \right\}^{1/2} \end{array} \right] = -\frac{q\,(\,N_{s10}\;f_1(V)\,\Delta E_1 + N_{s20}\,f_2(V)\,\Delta E_2)}{(\varepsilon_r\;\varepsilon_0\;N_d\;K_B\,T)^{1/2}}. \tag{4}$$

We get an equation that describes the equilibrium state for every voltage level. It contains all parameters that characterize the grain boundary and allows to numerically determining the barrier potential behaviour as a function of applied voltage for different parameters who characterize a single junction barrier. This equation has no adjustable parameters.

3. Results

The numerical solution of the previous equation is done for the illustrative forms given in Figure 1.

Figure 2 is a plot of the computed barrier height versus the voltage bias for different positions of E_2 level with respect to the valence band E_v. From this result, it is concluded that the barrier height $\phi(v)$ and the breakdown voltage per grain boundary are sensitive to position of traps level E_2.

Figure 3 and Figure 4 show the computed barrier height versus the voltage bias, respectively, for different values of N_d and N_{S10}. This results are evident if we consider the equation (4) for V=0.

Figure 5 is a plot of the barrier height $\phi(v)$ for differents N_{S20} values. It is concluded that the barrier height behaviour versus voltage bias and the nonlinearity coefficient depends strongly of the E_2 level density. The decrease of the barrier height became more uniform when there is not a high density of states at E_2 level.

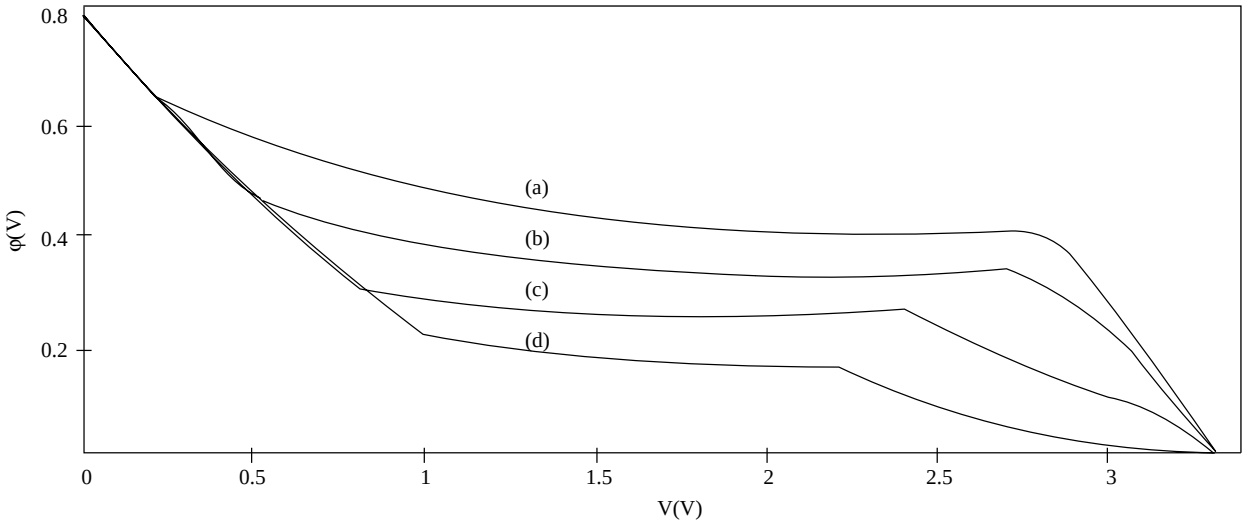

Figure 2. The barrier height versus voltage for T = 298 K, ε_r=8.5, N_{S10}= 5.35×10^{12} Cm^{-2}/eV, N_{S20} = 3.5×10^{12} Cm^{-2}/eV, N_d= 10^{17}cm^{-3}, ΔE_1 = ΔE_2 =0.2 V: (a) E_2 = 0.2 V, (b) E_2 = 0.5 V, (c) E_2 = 0.8 V, (d) E_2 = 1 V.

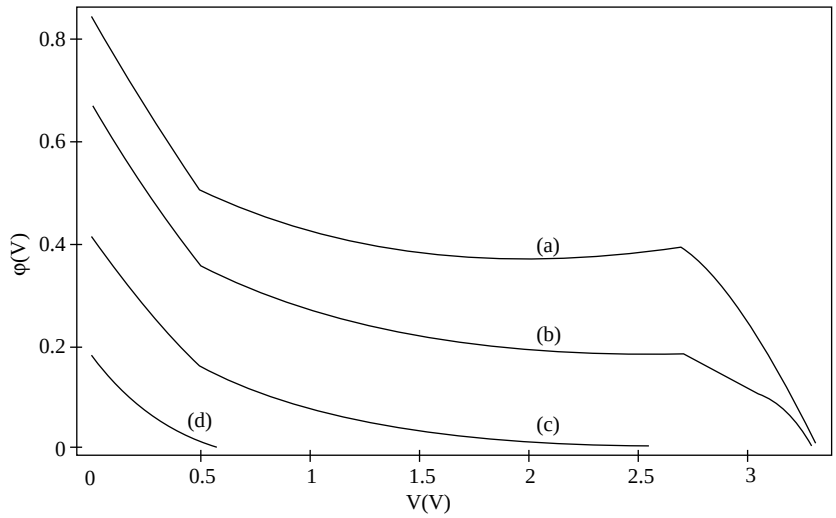

Figure 3. The barrier height versus voltage for $T = 298$ K, ε_r =8.5, $N_{S10} = 5.35\times10^{12}$ Cm^{-2}/eV, N_{S20}= 3.5×10^{12} Cm^{-2}/eV, $\Delta E_1 = \Delta E_2$ =0.2 V: (a) N_d=8×10^{16} Cm^{-3}, b) N_d=10^{17} Cm^{-3}, c) N_d=2×10^{17} Cm^{-3}, d) N_d=5×10^{17} Cm^{-3}.

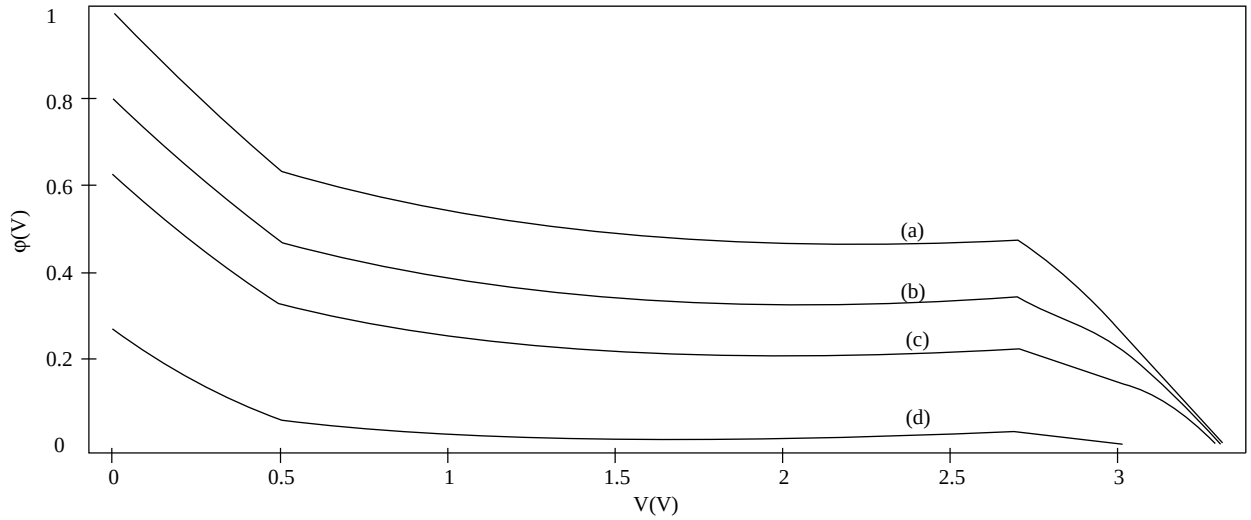

Figure 4. The barrier height versus voltage for $T = 298$ K, ε_r=8.5, $N_d = 10^{17}$ cm^{-3}, $N_{S20} = 3.5\times10^{12}$ Cm^{-2}/eV, $\Delta E_1 = \Delta E_2 = 0.2$ V: (a) $N_{S10} = 6\times10^{12}$ Cm^{-2}/eV, b) $N_{S10} = 5.35\times10^{12}$ Cm^{-2}/eV, c) $N_{S10} = 4.7\times10^{12}$ Cm^{-2}/eV, d) $N_{S10} = 3\times10^{12}$ Cm^{-2}/eV.

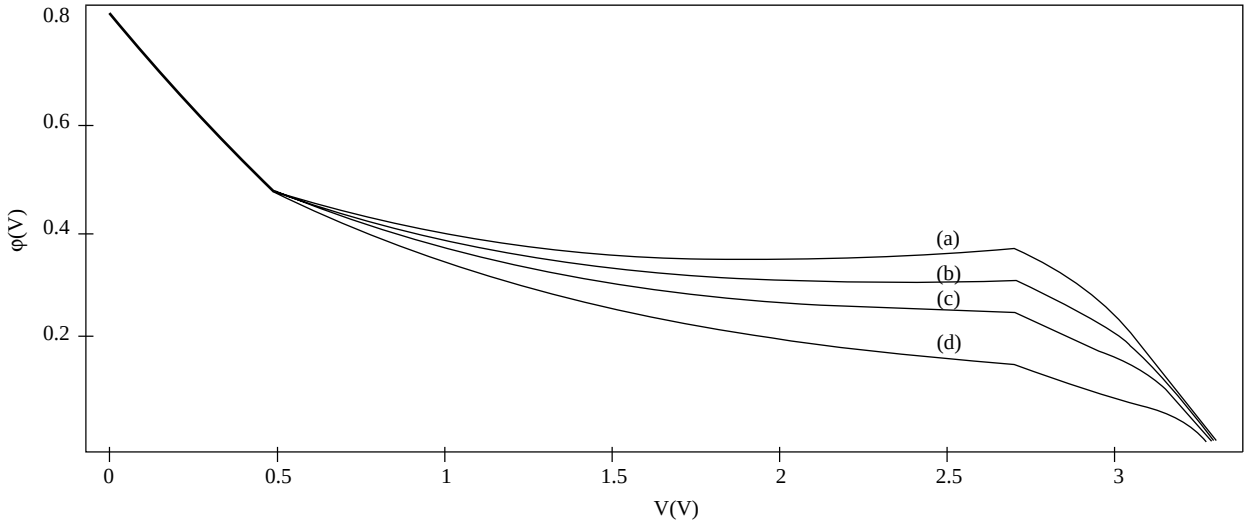

Figure 5. The barrier height versus voltage for $T = 298$ K, $\varepsilon_r = 8.5$, $N_d = 10^{17}$ cm^{-3}, $N_{S10} = 5.35{\times}10^{12}$ Cm^{-2}/eV, $\Delta E_1 = \Delta E_2 = 0.2$ V: (a) $N_{S20} = 6.2{\times}10^{12}$ Cm^{-2}/eV, b) $N_{S20} = 5.8{\times}10^{12}$ Cm^{-2}/eV, c) $N_{S20} = 5.3{\times}10^{12}$ Cm^{-2}/eV, d) $N_{S20} = 4.5{\times}10^{12}$ Cm^{-2}/eV.

4. Conclusions

The resulting model is consistent with the experimental observations in the case of ZnO, $TiO_2$and SnO_2-based varistors [6–9]. It makes plausible our hypothesis on the existence of two types of the traps levels and on the variation of their respective occupation. The one traps level serve to the formation of the barrier at zero bias and the other serve as relay to the generation of electrons-hole pairs responsible of the abruptly decrease of the barrier height from a critical voltage. From this threshold voltage which depends on the position of the unoccupied traps level, the equality $Q_+ = Q_S$ cannot be maintained and the barrier collapse.

Acknowledgements

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