Phonon-assisted tunneling mechanism of conduction in SnO_2 and ZnO nanowires

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ABSTRACT

Non-linear temperature-dependent current-voltages characteristics of SnO_2 nanowires presented by other authors are explained by the model based on phonon-assisted tunneling (PhAT) theory. It is shown that the PhAT model can explain the variation of current with temperature in all measured temperature range from 10 to 200 K over a wide range of electric fields. From the fit of experimental data with the theory the density of states in the interface layer is derived and electron-phonon interaction constant is estimated

Keywords: nanowires, resistivity, tunneling, tin oxide, zinc oxide

1 INTRODUCTION

Recently Ma et al. have presented the results on charge–carriers transport studies of a single SnO_2 [1] and ZnO nanowires [2]. It was found that resistivity of the single SnO_2 nanowire increases slowly with decreasing temperature from room temperature to 50 K, and increases rapidly below 50 K. The temperature dependence of the resistance followed the relation $\ln R \sim T^{-1/2}$. The authors of Ref. [1] asserted that the transport of the electrons in the nanowires is dominated by the Efros-Shklowskii variable-range hopping (ES-VRH) process [3]. However, the characteristic ES's temperature obtained from the slope of relation $\ln\rho \approx T$ of 231 K for SnO_2 nanowire was much higher than in the previously determined for ES-VRH behavior [3, 4]. For the ZnO nanowire case the Coulomb gap in the density of localized states near the Fermi energy was found abnormally big – about 0.8 eV when a few millivolts estimated by other authors [5]

In a recently published paper by Park et al [6] the temperature-dependent *I-V* characteristics in the temperature region of 70-293 K have been explained by Schottky emission but the results at lower temperatures the authors of [6] assigned as Fowler-Nordheim tunneling. Thus, for explanation of temperature dependent *I-V* data and resistivity dependence on temperature in these oxides different mechanisms, such as VRH, Schottky emission and tunneling, are involved.

We would like to show that in Ref. {1, 2, 6] presented data both in high and low temperature region can be explained by the unique phonon-assisted theory has earlier been used to explain similar results obtained for oxides and other dielectrics [7, 8]. Therefore, in this report we present an explanation of current dependence on temperature and electric field measured in ZnO and SnO_2 nanowires [1, 2] and in single ZnO nanorods [6] with the assumption that free charge carriers creation occurs due to the phonon-assisted tunneling from localized states in metal-oxide interface.

2 THEORY AND COMPARISON WITH EXPERIMENT

We assume that a source of charge carriers are the local electronic states in the oxide-electrode interface layer, the electrons from which emerged to the conduction band of the oxide due to electric field induced phonon-assisted tunneling. If electrons released from these centers dominate the current through the crystal then the current *I* will be proportional to the electron released rate *W* and the density of the traps *N*, i.e. $I \infty NW$. On this basis we will compare the current dependencies on field strength measured at different temperatures extracted from Ref. [1] with the calculated tunneling rate *W* dependencies on field strength *E*.

The temperature- and field-dependent tunneling rate *W(E,T)* was computed using the phonon–assisted tunneling theory [9] by the following equation:

$$W_1 = \frac{eE}{(8m^*\varepsilon_T)^{1/2}}[(1+\gamma^2)^{1/2} - \gamma]^{1/2}[1+\gamma^2]^{-1/4}$$
$$\exp\{-\frac{4}{3}\frac{(2m^*)^{1/2}}{eE\hbar}\varepsilon_T^{3/2} \times$$
$$[(1+\gamma^2)^{1/2} - \gamma]^2[(1+\gamma^2)^{1/2} + \frac{1}{2}\gamma]\}, \quad \gamma = \frac{(2m^*)^{1/2}\Gamma^2}{8e\hbar E\varepsilon_T^{1/2}}. \qquad (1)$$

Here $\Gamma^2 = 8a(\hbar\omega)^2(2n+1)$ is the width of the center absorption band, with $n=[\exp(\hbar\omega/(k_BT))-1]^{-1}$, where $\hbar\omega$ is the phonon energy, $\hbar$ is Dirac's constant, ε_T is the energetic depth of the center, *e* is the electron charge, and *a* is the electron-phonon interaction constant.

The comparison of *I-V* data measured at low temperatures for SnO_2 nanowire (from Figure 4a in [1]) with theoretical *W(E)* dependencies is shown in Figure 1.

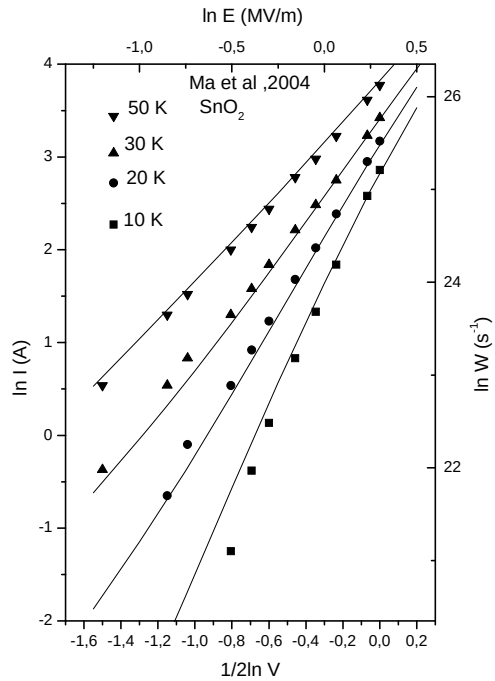

Figure 1: The comparison of *I-V* data for SnO_2 nanowire (from Figure 4a in [1]) with theoretical *W(E)* dependencies calculated using parameters:
a = 1, ε_T = 10 meV, $\hbar\omega$ = 2 meV, m* = 0.65m_e

The *W(E)* dependencies were calculated using for the electron effective mass the value of 0.65 m_e. For the phonon energy, the value of 1.6 meV, for the ε_T the value of 14 meV were selected. The electron-phonon coupling constant *a* was chosen so as to get the best fit the experimental data with calculated dependencies, on the assumption that field strength for tunneling is proportional to square root of applied voltage. As is seen from Figure 1, the theoretical *W (E)* dependencies fit well to the experimental data for all range of measured temperatures. It is worthwhile to mention that the theory describes well the measured *dI/dV* dependencies on field strength (see Figure 2).

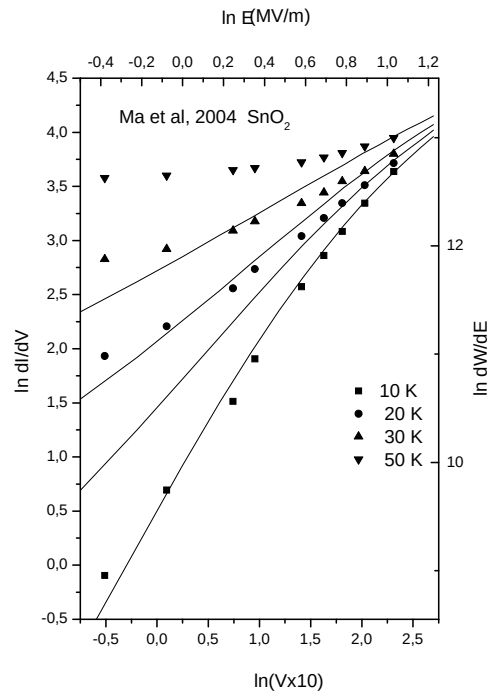

Figure 2: The fit of *dI/dV* dependencies extracted from [1] with *dW/dE* vs *E* calculated for the same parameters as in Figure 1.

In Fig. 3 the results of current dependence on temperature in single ZnO nanorods measured by Park et al [6] fitted to theoretical *W(T)* dependencies are shown. We want to mention that authors of [6] these dependencies above 70 K have explained by Schottky emission, meanwhile the results below that temperature assigned to FN tunneling. As is seen from comparison the phonon-assisted tunneling theory describes well the results over all measured temperature range.

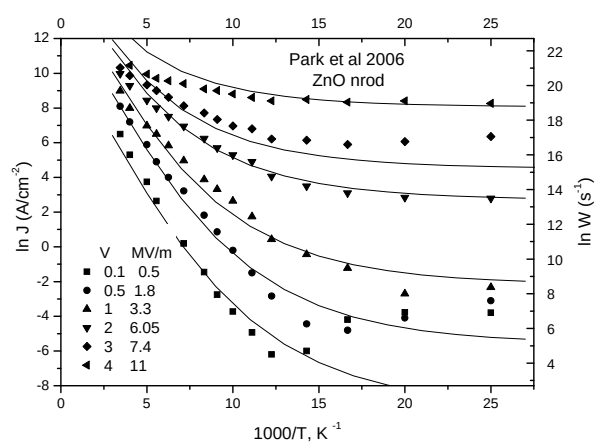

Figure 3: Current vs *1/T* for ZnO nanrods from [6] fitted to *W(T)* vs 1/T calculated using parameters:
a = 1.2; ε_T = 0.12; . $\hbar\omega$ = 16 meV, m* = 0.35m_e.

The field strengths for tunneling were found to be in the range from 0.55 MV/m to 11 MV/m. From the relation $I = eSNW$, where S is the area of the electrode, the surface trap density N can be estimated. From the results in Fig. 3 the surface trap density was found to be equal to $N \sim 10^{14}$ cm^{-2}.

We want to note that on the basis of the phonon-assisted tunneling model is comprehensible not only temperature dependence of current (resistivity), but also temperature independent behavior of current observed in low temperatures region. This assertion is partially confirmed by results presented in Figure 3, and for more clarity in Figure 4 we show the comparison of temperature – dependent conductivity (1/R) from inset in Figure 2 [6] with tunneling rate dependence on T. Below ~ 70 K resistance R changed very little with 1/T meanwhile in the temperature range of 70-293 K lnR linearly increased with *1/T*.

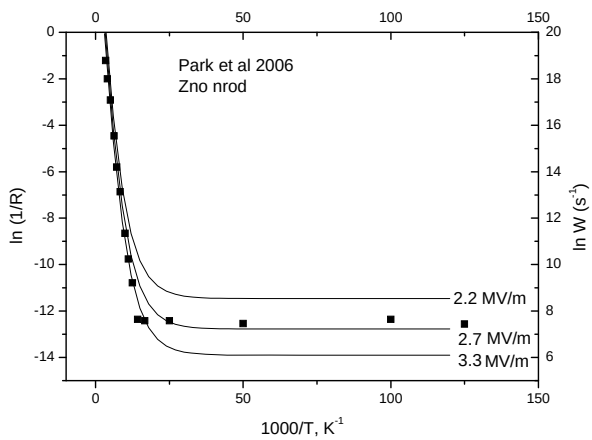

Figure 4: The ln (1/R) vs *1/T* from inset in Fig. 2 [6] fitted to *W(T)* vs *1/T* calculated using the same parameters as in Figure 3.

The fit of these data in coordinates of ln(1/R) versus *1/T* with theoretical ln*W(T)* versus *1/T* dependence shows a very good coincidence of experimental data and theoretical curve. The physical essence of independence of *W(T)* on temperature in the low temperature region is that at low temperatures the phonons are "frozen" and in the regime of low temperatures the phonon-assisted tunneling, as well as F-N ones, becomes temperature-independent process.

3 CONCLUSIONS

In summary, the phonon-assisted tunneling model enables to explain the peculiarities of temperature dependence current in oxide nanostructures, such as strong temperature dependence at high temperatures and less dependence on ones in the region of low temperatures. The variation of current-voltage curves on temperature describes the used equation also well. From the fit of experimental results with theory density of centres, which serve as a source of the free carriers, was found to be equal to 10^{14} cm^{-2} in ZnO nanorods.

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