Percolation electrical conductivity of $Ru_xTi_{1-x}O_2$ films in strong electric fields

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An experimental confirmation of the percolation electrical conductivity model of disordered materials in strong electric fields was obtained for the first time. According to this model, the field dependence of the electrical conductivity has a form close to the Frenkel-Pohl law but with a coefficient in the exponent that characterizes the degree of disorder.

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According to the percolation electrical conductivity model the *I-V* characteristics of amorphous and compensated crystalline semiconductors have a form close to the Frenkel-Pohl law but with a different coefficient in the exponent, which can depend on the degree of disorder.[1] However, available literature data on the field dependence of the electrical conductivity of such materials do not permit an unambiguous interpretation of the experimental results within the framework of this model, and no direct verification of it on model specimens has been done despite the importance of the percolation model of conductivity.

In this paper we report the results of a study of the *I-V* characteristics of $Ru_xTi_{1-x}O_2$ solutions with an incomplete degree of crystallinity, which are formed in the TiO_2-RuO_2 system, where TiO_2 is a semiconductor with a wide forbidden band gap ($E_g \approx 3.0$ eV) and RuO_2 is an oxide with metallic conductivity [1)].

It was shown earlier that for values of $x > x_c = 0.25$ an infinite cluster appears in these oxides, and the conductivity of the films becomes "quasi metallic" because of the presence of a finite (of the order of kT) mobility gap that is caused by their incomplete degree of crystallinity.[3] Therefore, the nonohmic conductivity in strong electric field ($E \sim 10^4$ V/cm) was investigated in oxides with a value $x < x_c$. Figure 1 shows the static *I-V* characteristics of the studied films. A transition to the intermediate state occurs as a result of reaching the threshold potential V_{thr}; the V_{thr} value is determined by the concentration of the ruthenium component. The samples go over to the final, stable state as a result of increasing the current density. It should be noted that in the pulsed measurement mode the transition occurs without an intermediate stage.

The composition dependence of V_{thr} (Fig. 2) has the following interesting properties: its extrapolation to the value $x = 0$ gives the switching potential $V_{thr} = 2.9$ V for TiO_2, which almost coincides with E_g, and the $V_{thr} = 0$ value is obtained for $x \geqslant x_c$, i.e., in the region where the infinite cluster exists. Thus, the V_{thr} value is determined by the finite clusters and hence by the dimensions of the large-scale fluctuations of the band boundaries whose amplitude is comparable to the forbidden band gap for TiO_2. A possible switching mechanism in these materials, which is associated with an increase in the carrier density due to electron transitions from deep levels to a state near

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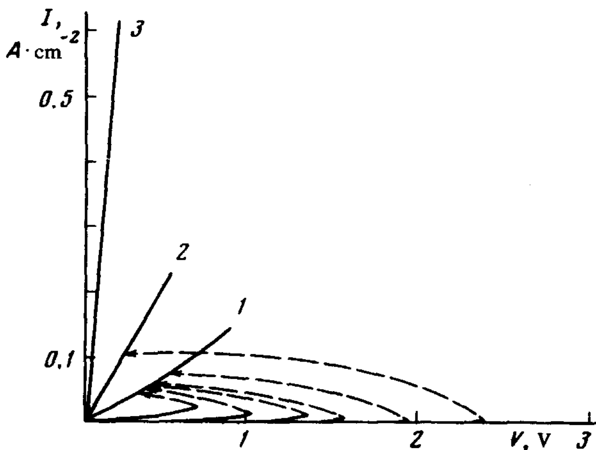

FIG. 1. I-V characteristics of $Ru_xTi_{1-x}O_2$ films: $x = 0.001$, $x = 0.005$, $x = 0.01$, $x = 0.03$, $x = 0.05$, and $x = 0.08$. The switching potential decreases with increasing x. 1, 2—intermediate state; 3—final stable state.

the flow level in the potential wells produced by large-scale fluctuations of the doping impurity concentration, was examined in Ref. 4.

At prethreshold potentials the I-V characteristics satisfy the relation $I \sim \exp\beta E^{1/2}$ and the coefficient β increases with increasing x (Fig. 2). As $x \to 0$ $\beta/e = 1.45 \times 10^{-3}$ $V^{1/2}\,cm^{1/2}$, which is almost identical to the value obtained in Ref. 5 for the Ti-TiO_2 oxide film-Al (Au) structure, and consequently the field dependence of the I-V characteristic does not depend on the electrode. However, the Frenkel-Pohl model, proposed in Ref. 5 for interpreting the I-V characteristic, does not agree with the following results for our samples: 1) the experimental values of β exceed by an order of magnitude the values calculated from the known formula $\beta = (e/\pi\epsilon\epsilon_0)^{1/2}$; 2) measurements of the dielectric constant of the studied films showed that as x increases it increases rapidly with the model for the flow of conducting finite clusters in a dielectric medium,[6] and consequently the exponential coefficient should decrease when the Frenkel-Pohl law is satisfied. This contradicts the experimental results. Thus, the field dependence of the I-V characteristics of the studied samples satisfies the percolation conductivity model in strong electric fields.

Since $\beta = (CeaU)^{1/2}$, where a and U are, respectively, the radius and amplitude of

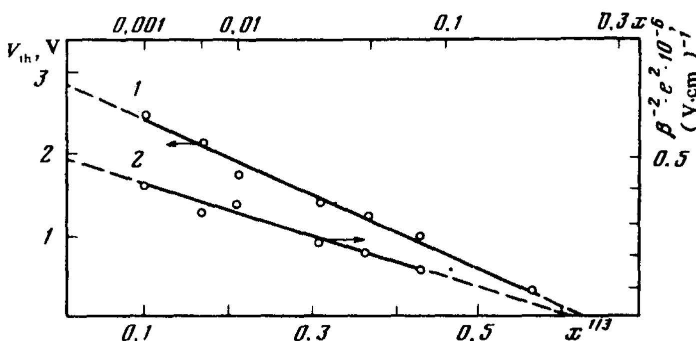

FIG. 2. Dependence of switching potential V_{thr} and coefficient β on the film composition.

the large-scale fluctuations and C is an unknown numerical coefficient,[1] a comparison of the smallest typical fluctuation, which bends the bands by an amount of the order of E_g,[7] and its value determined from β, makes it possible to calculate the coefficient: $C = 0.20$.

The given experimental results confirm the conclusions of Ref. 1 concerning the field dependence of percolation conductivity in disordered systems. The necessary condition for observing the effects predicted in this paper, specifically, the presence of large-scale fluctuations whose amplitude is comparable to the activation energy of ohmic conductivity, is satisfied in the investigated oxide films.

[1)]The sample preparation method was described in Ref. 2. Five-μm-thick films were deposited on a titanium substrate, and a mercury electrode was used as the second anode.

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