UNCONVENTIONAL METAL-INSULATOR TRANSITION IN Re_xSi_{1-x}

E.K. Arushanov[1, 2], K.G. Lisunov[1*], J. Schumann[2], and H. Vinzelberg[2]

[1]*Institute of Applied Physics, Academy of Sciences of Moldova, 5, Academiei str., MD-2028, Chisinau, Republic of Moldova*
[2]*Leibniz-Institut für Festkörper und Werkstoffforschung Dresden - IFW Dresden, 20, Helmholtzstr., D-01069, Dresden, Germany*
[*]*Corresponding author, e-mail: kgl-is-here@rambler.ru*
(Received 13 September 2010)

Abstract

Low-temperature resistivity of the amorphous Re_xSi_{1-x} thin films at $x < x_c$ is governed by the Mott and the Shklovskii-Efros variable-range hopping (VRH) conductivity mechanisms, where $x_c \approx 0.327$ corresponds to the metal-insulator transition (MIT). The critical exponent of the dielectric permittivity, $\eta = 2.1 \pm 0.2$, is found to be in agreement with the theoretical prediction, $\eta = 2$. The critical exponent of the correlation length, $\nu \approx 0.8 - 1.1$ close to the expected value of unity is obtained under an assumption of a strong underbarrier scattering of hopping charge carriers.

1. Introduction

Transition metal silicides have gained considerable attention in the last decades as components in silicon-based microelectronics. Their favorable electrical properties together with a high thermal stability, as well as corrosion resistance against attack of an oxidizing ambient, have made a number of them attractive for use in very-large-scale integration circuits as gates and interconnects and as reliable high-barrier Schottky or ohmic contacts of low contact resistance [1]. Recently, amorphous binary Re_xSi_{1-x} thin films were prepared [2, 3]. The low-temperature transport of amorphous Re_xSi_{1-x} thin films was studied in the metallic side of the metal-insulator transition (MIT) [3]. The purpose of the present work is to investigate hopping conductivity and its critical behavior in the insulating phase of the amorphous rhenium silicide thin films near the MIT.

2. Results and discussion

Amorphous Re_xSi_{1-x} thin films were prepared by co-sputtering from Re and Si targets in a cryopumped HV system onto unheated oxidized Si wafers. The investigated films had compositions x = 0.285 (#1), 0.293 (#2), 0.313 (#3), 0.315 (#4), 0.320 (#5), 0.324 (#6), 0.328 (#7), 0.337 (#8), and 0.351 (#9). The film thickness was between 60 and 150 nm. The amorphous structure was checked by electron diffraction and calculation of the radial density distribution function [4]. The resistivity ρ was measured using conventional dc techniques. As can be seen in Fig. 1, the low-temperature resistivity exhibits an activated behavior with the slopes of the plots in Fig. 1 depending on T, which suggests variable-range hopping (VRH) conduction mechanisms [5].

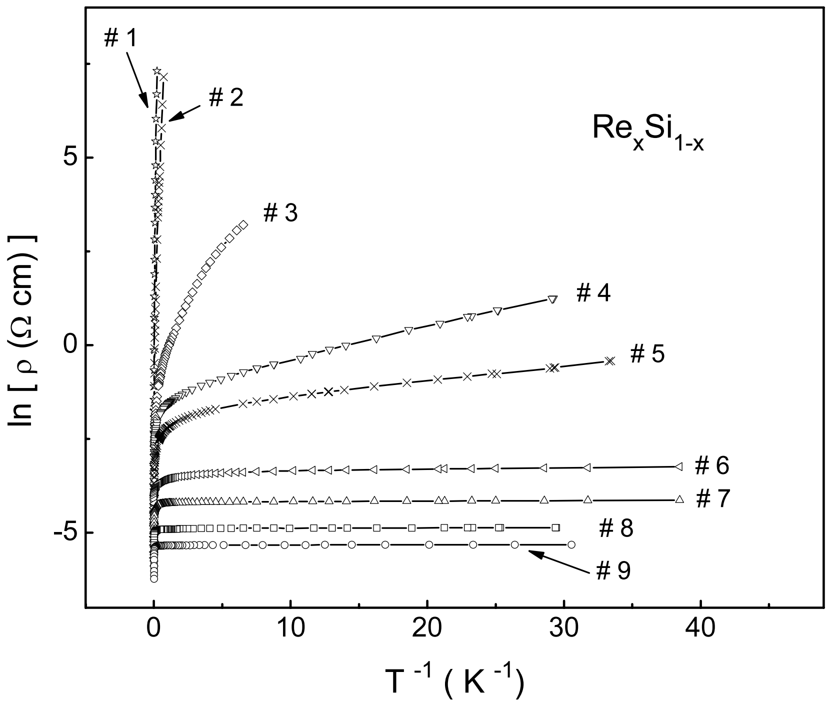

Fig. 1. Temperature dependence of the investigated Re_xSi_{1-x} samples #1–9.

The resistivity in the region of the VRH conduction is given by the universal expression

$$\rho(T) = AT^{m} \exp[(T_{0p}/T)^{1/p}], \quad (1)$$

where A = const, $m = 1/p$ (in the vicinity to MIT the value of m may be diminished [6]), $p = 4$ and 3 for 3D and 2D Mott VRH mechanisms, respectively, and $p = 2$ for the Shklovskii-Efros (SE) VRH conductivity, connected to the Coulomb gap, Δ, in the density of the localized states. The characteristic temperature in Eq. (1), $T_{0p} \sim a^{1-p}$ for the Mott VRH (p = 4 and 3) and $T_{02} \sim (\kappa\, a)^{-1}$ for the SE VRH conductivity regimes, where a is the localization radius of the charge carriers and κ is the dielectric permittivity [5]. Width of the 3D Coulomb gap can be found with the expression $\Delta \approx 0.5\,(T_{02}T_{v2})^{1/2}$, where T_{v2} is the onset temperature of the SE VRH conduction regime [5].

Near MIT given by the value of $x = x_c$ a critical behavior of $\kappa = \kappa_0\,(1 - x/x_c)^{-\eta}$ and $a = a_0\,(1 - x/x_c)^{-\nu}$ is expected [6], where η and ν are critical exponents of κ and a, respectively, and κ_0 and a_0 are (constant) values of κ and a far from MIT, respectively. Additionally, it can be shown that, in conditions of a strong underbarrier scattering (UBS) of the hopping carriers by intermediate centers [7], the critical behavior of a is given by the expression $a \approx b_0\,(1 - x/x_c)^{-5\nu/2}$ (b_0 = const). The values of ν = 1 and η = 2 have been predicted theoretically; the observed values of ν and η are grouped closely around the theoretical predictions mentioned above [6].

Critical behavior of the parameters Δ and T_{0p}, which can be extracted from the experimental data, is given by the relations $\ln\Delta = \ln\Delta^* + \nu_\Delta \ln(1 - x/x_c)$ and $\ln T_{0p} = \ln T_{0p}^* + \nu_p \ln(1 - x/x_c)$, where Δ^* and T_{0p}^* are constants,

$$\nu_\Delta = \eta\, d/(d - 1), \quad (2)$$

$$\nu_2 = \nu + \eta,\ \nu_3 = 2\,\nu, \text{ and } \nu_4 = 3\,\nu \text{ (no UBS)}, \quad (3)$$

and

$$\nu_2 = 5\nu/2 + \eta,\ \nu_3 = 5\,\nu, \text{ and } \nu_4 = 15\,\nu/2 \text{ (strong UBS)}. \quad (4)$$

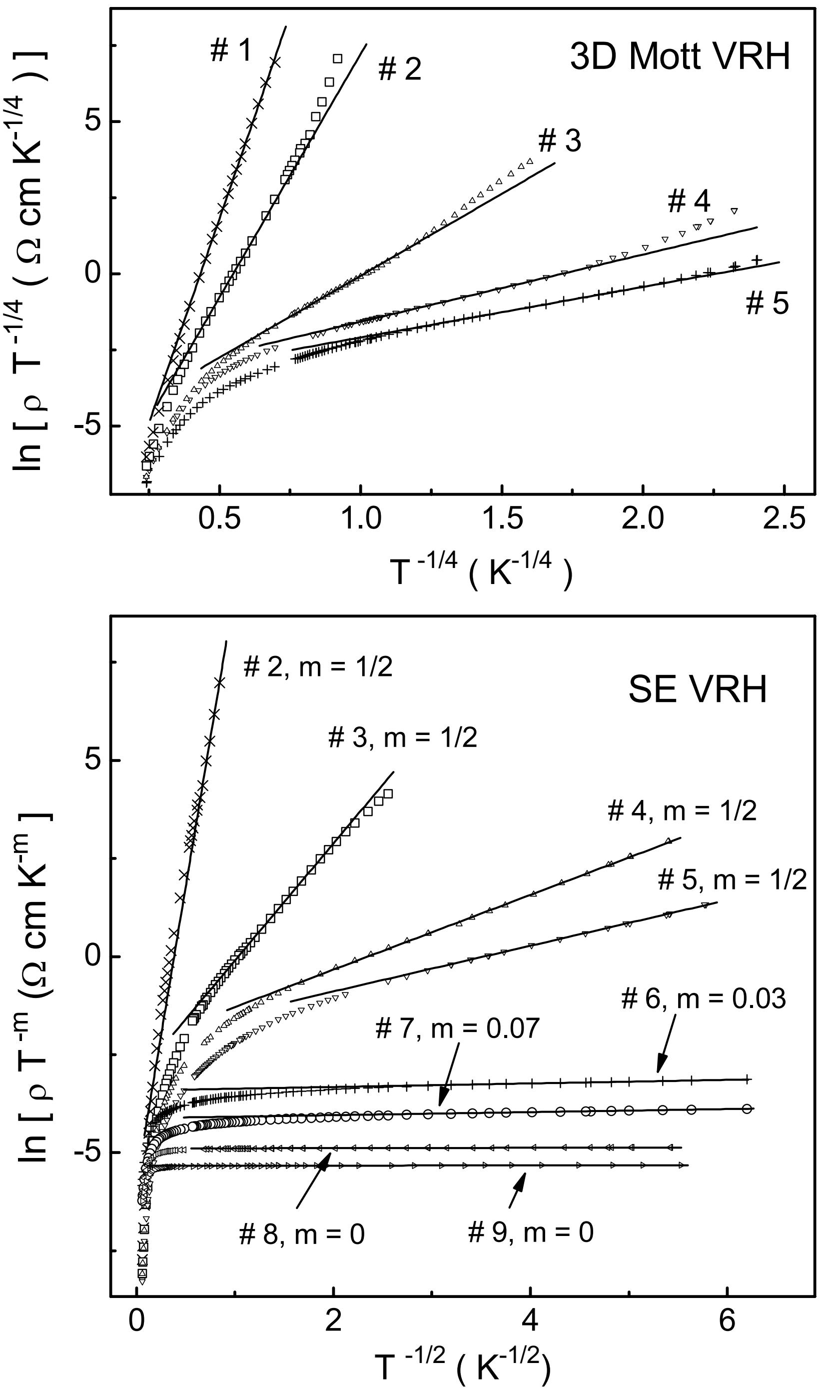

Fig. 2. Plots of ln(ρ $T^{-1/4}$) vs. $T^{-1/4}$ (top panel) and ln(ρ T^{-m}) vs. $T^{-1/2}$ (bottom panel) for the investigated samples.

The results of the analysis of the resistivity in Fig. 1 with Eq. (1) are summarized in Fig. 2. It can be seen a general tendency of transformation of the 3D Mott VRH conductivity (top panel of Fig. 2) into the SE VRH conduction (bottom panel) with lowering the temperature. In addition, in #6–9 the value of *m* is diminished, as can be expected close to MIT, whereas the slope of the plots for #7–9 is negligible and is more characteristic of an activationless (metallic) behavior.

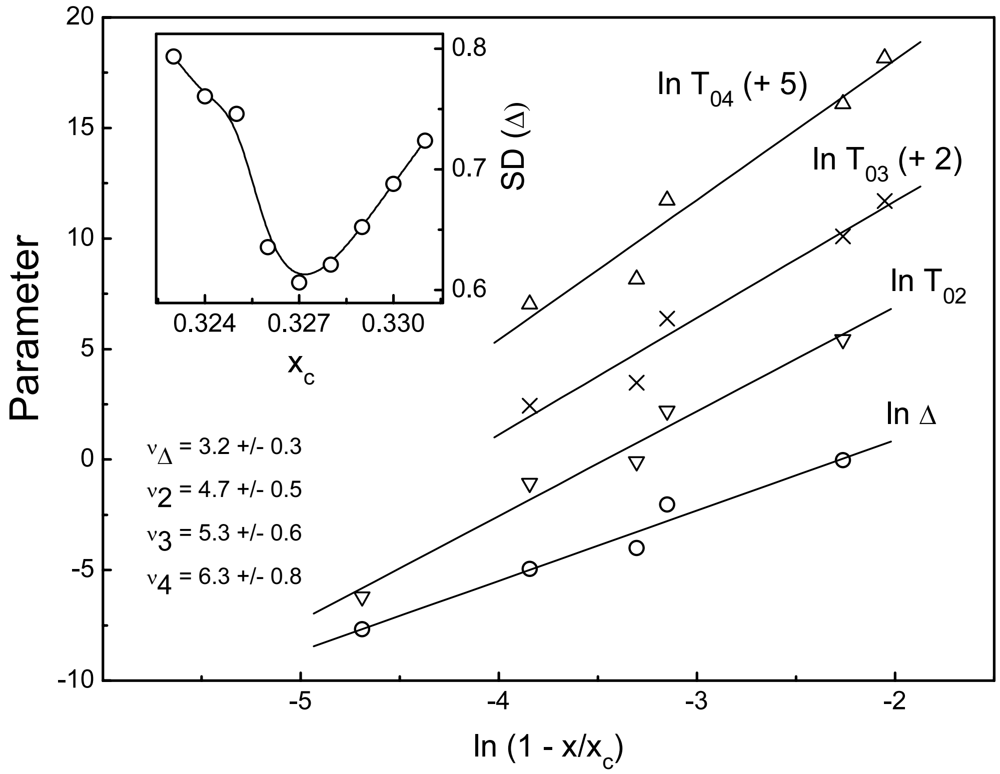

Fig. 3. Dependences of $\ln\Delta$ and $\ln T_{0p}$ (Δ in meV, T_{0p} in K and $p = 2 - 4$) on $\ln(1 - x/x_c)$, fitted with the linear function (the straight lines). Some of the plots are shifted along the vertical axis by the values given in parenthesis. Inset: standard deviation (SD) of the linear fit of the plots of $\ln\Delta$ vs. $\ln(1 - x/x_c)$ represented as a function of x_c. The line is to guide the eye.

The critical behavior of Δ and T_{0p} is exhibited in Fig. 3. Here T_{02} and T_{04} are obtained from the plots in Fig. 2 and T_{03} from the similar plots for the 2D Mott VRH regime (not shown), whereas Δ is calculated as described above [see remarks below Eq. (1)]. The value of $x_c \approx 0.327$ is found by minimization of the standard deviation (SD) of the plots of $\ln\Delta$ vs. $\ln(1 - x/x_c)$ by variation of x_c (inset to Fig. 3). Using the data of ν_Δ and $\nu_2 - \nu_4$ collected in Fig. 3, one finds with Eqs. (2)-(4): $\eta = 1.6 \pm 0.2$ (2D hopping regime) and 2.1 ± 0.2 (3D hopping regime), where the latter agrees better with the theoretical prediction ($\eta = 2$); when the effect of UBS is neglected, the values of $\nu \approx 2.1 - 2.6$ are far from the expected value of $\nu = 1$; eventually, assuming strong UBS, $\nu \approx 0.8 - 1.1$ is in a good agreement with the predicted value of $\nu = 1$ and with the literature data [6].

3. Conclusions

The low-temperature resistivity of the amorphous Re_xSi_{1-x} thin films is governed by the VRH mechanism of the Mott and the Shklovskii-Efros types. The characteristic VRH temperatures T_{0p} and the width of the Coulomb gap Δ demonstrate a critical behavior as x tends to $x_c \approx 0.327$, which corresponds to the metal-insulator transition. The critical exponent of the dielectric permittivity, $\eta = 2.1 \pm 0.2$, is close to the theoretical prediction ($\eta = 2$). The critical exponent of the correlation length, $\nu \approx 2.1 - 2.6$, exceeds the predicted one, $\nu = 1$, suggesting a strong underbarrier scattering of the hopping carriers. By taking into account this effect, $\nu \sim 0.8 - 1.1$ is found in agreement with the theoretical prediction and the literature data.

References

[1] H. Lange, Phys. Status Solidi (b), 201, 3, (1997).
[2] H. Vinzelberg, A. Heinrich, C. Metz, and J. Schumann, Proc. 6th Int. Conf. "Hopping and Related Phenomena", ed. by O. Millo and Z. Ovadyahu, Jerusalem, 224, 1995.
[3] A. Heinrich, H. Vinzelberg, and C. Metz, Phys. Rev. B, 67, 035302, (2003).
[4] V. Borisenko, ed. by, Semiconducting Silicides, Springer, Berlin, 351, 2000.
[5] B.I. Shklovskii and A.L. Efros, Electronic Properties of Doped Semiconductors, Springer, Berlin, 416, 1984.
[6] T.G. Castner, in Hopping Transport in Solids, ed. by M. Pollak and B. Shklovskii, North Holland, Amsterdam, 3, 1991.
[7] B.I. Shklovskii and B.Z. Spivak, in Hopping Transport in Solids, ed. by M. Pollak and B. Shklovskii, North-Holland, Amsterdam, 271, 1991.