# Nonohmic hopping conductivity with variable-range hopping in crystalline silicon

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(Submitted 20 January 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 5, 248–249 (10 March 1987)

Experimental study of crystalline $n$-Si$\langle P \rangle$ showed that $l$, the length parameter which characterizes the nonohmic nature of the hopping conductivity with variable-range hopping, is a large value, appreciably exceeding the mean range of the hop, and that with decrease of the temperature $T$, this value increases in proportion to $l \sim T^{-n}$, where $n \approx 1$. This behavior is consistent with the predictions of the theoretical model and the numerical calculations {E. I. Levin and B. I. Shklovskiĭ, Fiz. Tekh. Poluprovodn. **18**, 856 (1984) [Sov. Phys. Semicond. **18**, 534 (1984)].

There is no unified theory on the nonohmic nature of the hopping conductivity with a variable hopping length, and an unambiguous choice among the various theories[6–8] cannot yet be made on the basis of the available experimental data.[1–5] This circumstance shows that further experiments must be carried out using a sample in which the conductivity mechanism in the ohmic region has been reliably established. As such a candidate we used samples of crystalline silicon doped with phosphorus, without any special compensation and with an electron density of $2.8 \times 10^{18}$ cm$^{-3}$ at 300 K. The previously published results[9] of a study of the ohmic conductivity of these samples showed that at low temperatures the electrical conductivity is achieved by means of a hopping conductivity with a variable hopping length:

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$$\sigma(T) = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^x\right], \qquad x = 1/2. \tag{1}$$

The exponent $x = 1/2$ shows that in the spectrum there are localized states of the parabolic quasigap at the Fermi level. With regard to the theoretical models, they were calculated for the case where the state density near the Fermi level is constant and the conductivity is described by expression (1) with $x = 1/4$ (the Mott law). The basic ideas, however, must not depend, in our view, on the value of $x$.

According to the theoretical models,[6-8] in electric fields higher than the ohmic threshold we have

$$\sigma(E,T) = \sigma(0,T)\exp\left[\frac{eEl}{kT}\right] \sim \exp\left[C\,\frac{eEr(T)}{kT}\right], \tag{2}$$

where $r(T) = (a/2)\xi_c$ is the maximum length of the hop at a constant temperature, $a$ is the localization length, and $\xi_c = (T_0/T)^x$ is the temperature factor in (1). In the theoretical calculations of the nonohmic conductivity it was assumed that $x = 1/4$. The largest discrepancy in the models is that of the coefficient $C$. The authors of Refs. 6 and 7 assumed that $C$, a constant, is equal to 0.17 and 0.8, respectively. On the other hand, it was shown in Ref. 10 that $C = C(T)$ and that in the interval $\xi_c$ from 15 to 30 we have $C = \alpha\xi_c$, where $\alpha = 10^{-2}$.

The experimental results are shown in Figs. 1 and 2. Figure 1 shows that accord-

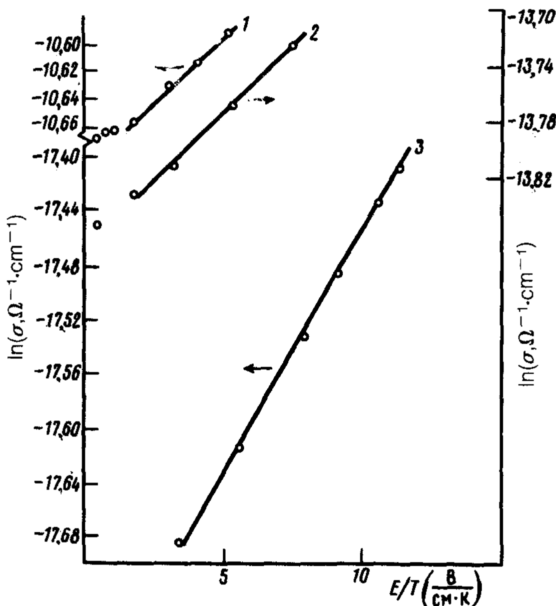


FIG. 1. Conductivity of one of the test samples versus the electric field at various temperatures: 1—4.23 K; 2—2.99 K; 3—1.99 K.

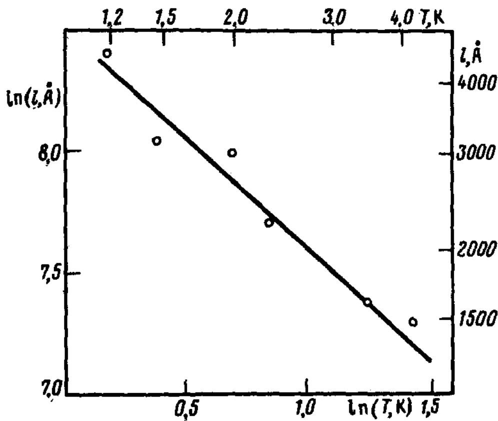


FIG. 2. Temperature dependence of the length parameter $l$ which characterizes the nonohmic nature of the hopping conductivity.

ing to (2), the plots $\ln \sigma(E)$ versus $E/T$ are described well by the straight lines, whose slope allows us to determine $l$. Experiments showed that $l \gg r(T)$. In the temperature range studied the values of $r(T)$ are $\approx$130–250 Å, whereas $l \approx$1500–4500 Å. With decrease of the temperature, $l$ increases in accordance with $l \sim T^{-n}$, where $n = 0.9 \pm 0.2$ (Fig. 2). (The values of $n$ close to unity were also found in Ref. 11 in the study of the nonohmic hopping conductivity in amorphous Ge–Cu films.) This result is inconsistent with the predictions of Refs. 6 and 7 and is consistent with the model of Ref. 10. Actually, if $C=$ const, then $l(T) \sim (a/2)\xi_c \sim T^{-x}$, where $x = 1/4$ or 1/2. On the other hand, according to Ref. 10, we have

$$l(T) = C(T)\, r(T) = \frac{a}{2}\xi_c\, (\alpha \xi_c) \sim T^{-2x} \ . \quad (3)$$

In our case, $x = 1/2$. Consequently, we have $l \sim T^{-1}$, in agreement with the experiment. Substituting $T_0 = 1000$ K and $a = 17$ Å (Ref. 9) in (3), we find $\alpha_{1/2} = 0.5$, a value two orders of magnitude higher than the theoretical value calculated for the case $x = 1/4$.

We wish to thank B. I. Shklovskiĭ for a discussion of the results.

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Translated by S. J. Amoretty