Mesoscopic effects in the hopping conductivity of thin films of amorphous silicon bombarded by ions

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The transverse hopping conductivity has been studied in thin films ($L = 330$–440 Å) of amorphous silicon (a-Si) with a small contact area ($S = 8\times 8\,\mu\text{m}^2$). The a-Si films were produced by ion bombardment of crystalline silicon. The room-temperature conductivity fluctuates markedly from sample to sample. Histograms of the conductivity distribution among samples are studied. The nature of the asymmetry of the distribution function is determined by the thickness of the amorphous film. Oscillations in the conductivity are also observed as the temperature and an applied voltage are varied. The experimental results are interpreted in a model of the hopping conductivity involving 1D chains of defects connecting metal contacts.

1. INTRODUCTION

Below room temperature in amorphous semiconductors, charge is transported by electrons tunneling between localized states deep in the band gap. These states are generated by structural defects. In a 3D macroscopic system, the temperature dependence of this hopping conductivity is described well by the Mott formula[1]

$$\sigma(T)\propto \exp[-(T_0/T)^{1/4}],\quad T_0=16/kga^3, \tag{1}$$

where k is the Boltzmann constant, g is the density of states near the Fermi level, and a is the localization radius of an electron at a defect.

A convenient physical representation which describes the features of hopping transport and which, in particular, leads to expression (1) is the model of an infinite percolation cluster consisting of resistances connected between trapping centers.[2] The length scale of the uniformity of such a cluster (the size of its cell) can be estimated from

$$L_c\approx a(T_0/T)^{1/4}. \tag{2}$$

Assuming $g\approx 10^{19}\,\text{eV}^{-1}\cdot\text{cm}^{-3}$, $a = 3$ Å, and $T = 300$ K, we find $L_c \approx 3000$ Å.

If the sample size L is much smaller than L_c, the characteristics of the sample should not undergo self-averaging over a large number of realizations of the random configuration of the infinite cluster, and the properties of the system should be very different from those of a macroscopic sample. This behavior of a small sample with a hopping conductivity has been labeled "mesoscopic" by analogy with effects seen in microstructures based on samples with a "metallic" conductivity.[3,4] Pollak and Hauser[5] have suggested that in a sufficiently thin film the conductivity of an infinite cluster is shunted by rare isolated chains of defects which are anomalously close together. If the area of the sample is large, the optimum shunting chains will be those for which the product of the conductivity and formation probability is largest. Pollak and Hauser[5] invoked the presence of optimum chains in a successful effort to explain the temperature dependence of thin, large-area a-Si films. A detailed calculation of the transverse conductivity of a thin amorphous film was carried out in Ref. 6, where it was shown that the optimum chains are extremely long. The temperature dependence of the conductivity σ_∞ should be described by the formula

$$\ln(\sigma_\infty/\sigma_0)=-2(2L\lambda/a)^{1/2}, \tag{3}$$

where σ_0 is a pre-exponential factor, and λ satisfies the transcendental equation

$$\lambda=\ln(0{,}270\lambda/gkTaL^2). \tag{4}$$

Since the optimum chains are exponentially rare, expression (3) applies only to the case of a contact area $S> S_0$, where S_0 is the area per chain. In the opposite case ($S<S_0$), the current flow through the sample is determined by a limited set of the best-conducting (but not optimum) chains present in the sample. The number of such chains is $M\sim 1$, so in going from sample to sample we should expect fluctuations in M on the order of $M^{1/2}\sim 1$, i.e., a complete replacement of the group of leading chains which determine $\ln \sigma$. The typical value of S_0 for a-Si is[7] $10\times 10\,\mu\text{m}^2$. Statistical fluctuations in the logarithm of the conductivity have the consequence that a set of samples is characterized by a conductivity distribution $f(\ln \sigma)$.

Since the resistance of the various chains react in different ways to a change in some external agent (the temperature, a magnetic field, the potential on a gate electrode, etc.), their contributions to the conductivity of the structure may become redistributed. An external agent, like a switch from one sample to another, should thus initiate replacement of the chains which determine the individuality of the sample. Indeed, fluctuations in hopping conductivity have been observed in field-effect transistors when the gate voltage and the strength of the magnetic field vary.[8–10] Attempts to interpret the results on the basis of the model of an amorphous thin film,[5] however, have been unsuccessful.[8] Our purpose in the present study was to learn about the transverse conductivity of thin films ($L\ll L_c$) of amorphous silicon (a-Si) of small area ($S<S_0$) produced by ion bombardment.

In Sec. 2 we describe the test samples, the procedure for preparing them, and the measurement procedure. In Sec. 3 we analyze experimental histograms of the distribution of the logarithm of the conductivity among the a-Si samples, and we compare the results with theoretical predictions. Section 4 is a study of how the temperature and a bias voltage affect the conductivity of the structures.

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2. PREPARATION OF THE SAMPLES AND EXPERIMENTAL PROCEDURE

Figure 1 is a schematic diagram of the test structure. Amorphous layers with thicknesses $L = 330$ and 440 Å were formed on p-type Si⟨111⟩ substrates with an acceptor concentration $N_a \approx 3\cdot 10^{19}$ cm^{-3} by implanting Ge^+ ions through a SiO_2 film ($L_{SiO_2} \approx 500$ Å). The thicknesses of the layers produced were monitored by Rutherford backscattering of He^+ ions in a grazing-reflection geometry. To produce a sharper a-Si/Si interface we heated the structure at $T = 400$ °C for 20 min in a H_2 atmosphere. An ohmic upper contact (of Al), with an area $S = 8\times 8$ μm^2, was formed on the surface of the a-Si by photolithography. The lower electrode was the crystalline silicon substrate on which the Al layer was deposited. The use of a heavily doped material as substrate and the annealing of the structure at $T = 400$ °C make it possible to avoid a contribution from the resistance of the very defective transition layer at the a-Si/Si interface to the conductivity of the structure.[11]

The conductivity of these structures was measured in transverse geometry. To eliminate a nonohmic hopping conductivity, which was undesirable in several of the experiments, we usually kept the gate voltage below 50–100 mV. The differential conductivity of the samples was measured at a frequency of 11 Hz by a modulation procedure with synchronous detection.

For a comparison of the electrical characteristics, some structures with an a-Si thickness of 0.15 μm were prepared in parallel with the thin layers. The observation of the Mott law, typical of amorphous silicon, for $T < 300$ K in the structures with the thin a-Si layers leads to the conclusion that the contact resistance makes a negligible contribution to the conductivity of the structures.

3. DISTRIBUTION OF THE CONDUCTIVITY AMONG SAMPLES

A distinctive feature of the particular material selected for this study, i.e., amorphous silicon produced by ion bombardment, is that hopping conductivity can be observed at room temperature (curve *1* in Fig. 2). The Fermi level in a-Si is pinned in a region of localized states deep in the mobility gap (the localization radius is[12] $a = 3$ Å). For this reason, the conductivity involving localized states outweighs processes involving thermal activation of carriers above a threshold as the mechanism for current flow. This circumstance presents us with a unique opportunity for experimentally studying the statistics of mesoscopic fluctuations of the hopping conductivity among samples of identical geometry.

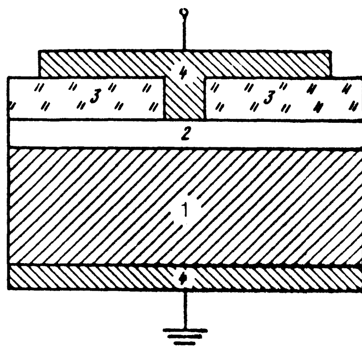

FIG. 1. Schematic diagram of the test structure. *1*—Heavily doped p-type Si substrate; *2*—a-Si; *3*—SiO_2; *4*—Al.

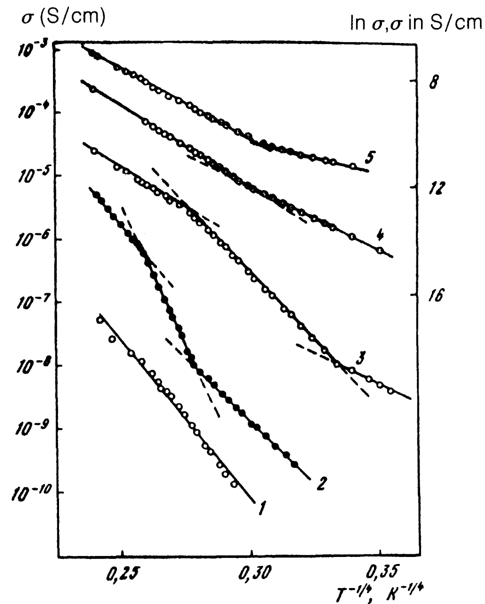

FIG. 2. Temperature dependence of the transverse conductivity. *1*—Thick a-Si film ($L = 1500$ Å); *2–5*—thin a-Si films ($L = 330$ Å) on heavily doped p-Si (transverse geometry).

The hopping charge transport is seen experimentally in doped crystalline semiconductors only at liquid-helium temperatures and below. In order to obtain reliable experimental data on the distribution $f(\ln \sigma)$ from the samples, it is necessary to take measurements on a large number of samples at a fixed temperature. This procedure obvious becomes very laborious and difficult at low temperatures. Accordingly, the experimental results which have been reported so far[8–10] are limited to studies of mesoscopic effects in a single sample as an external agent is varied. There has been no analysis of distributions among samples.

In the course of the conductivity measurements at room temperature of thin a-Si layers produced on one silicon wafer, it was found that $\ln \sigma$ varies from sample to sample, over the range from -16 to -4. The number of samples of a given thickness and a given contact area which were analyzed was on the order of 100. Histograms of the $\ln \sigma$ distribution were constructed by the following procedure. The overall range of the logarithm of the conductivity was partitioned into 12 intervals; the width of one interval was $\delta = 1$. We then determined the relative number of samples with $\ln \sigma$ values falling in a given interval $[\ln \sigma, \ln \sigma + \delta]$. The experimental histograms of the conductivities for two a-Si films with thicknesses $L = 330$ and 440 Å and an area $S = 8\times 8$ μm^2 are shown in Fig. 3. The dashed histogram here shows the conductivity of a thick a-Si film ($L = 1500$ Å). A study of $\sigma(T)$ showed that for $T < 300$ K the conductivity of the thick film has a temperature dependence which obeys the Mott law, (1) (Fig. 2); i.e., it is determined by a 3D percolation through an infinite cluster.

It turns out that the conductivity of thin a-Si layers is significantly higher than σ of a thick film (Fig. 3). This result is evidence that defects which shunt the infinite cluster appear at small thicknesses. Since the probability for the for-

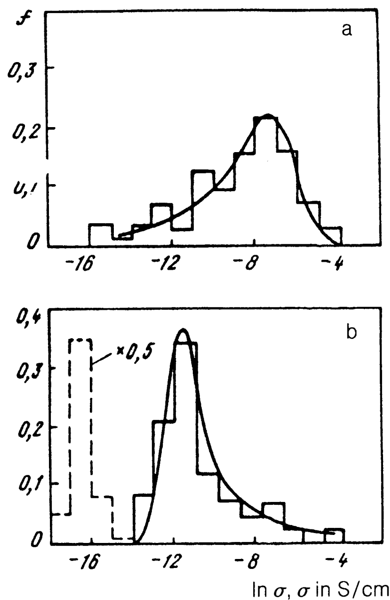

FIG. 3. Histograms of the distribution of the logarithm of the conductivity of a-Si among various samples at $T = 300$ K. a—$L = 330$ Å; b—440 Å. The smooth curves are theoretical approximations of the distribution $f(\ln\sigma)$. a—The values of the adjustable parameters are $g = 0.71\cdot 10^{19}$ $\mathrm{eV^{-1}\cdot cm^{-3}}$ and $\ln\sigma_0 = 41.2$; b—$g = 0.66\cdot 10^{19}$ and $\ln\sigma_0 = 24.5$. The dashed histogram is $\ln\sigma$ for a thick a-Si film ($L = 1500$ Å).

mation of such a chain is an exponential function of L (Ref. 6), a small change in the thickness of the a-Si film should lead to a substantial change in conductivity. Indeed, the experiments reveal a shift of the maximum on the distribution function by 1.5 orders of magnitude toward higher conductivities as the film thickness is reduced from 440 to 330 Å (Fig. 3).

It can be seen from Fig. 3 that the structures with the various a-Si thicknesses differ not only in the position of the maximum on the distribution function but also in the shape of the function $f(\ln\sigma)$. In the case of the thinner film ($L = 330$ Å), for example, the tail on the distribution stretches down to low conductivities. Such a tail is a specific 1D feature and is evidence of a hopping charge transport involving a small number (~ 1) of 1D chains of defects. Since the resistance of a chain is dominated by the few largest resistances, and the current lines cannot "circumvent" these high-resistance parts, the relative number of poorly conducting samples is high; this circumstance is reflected in the distribution function.

As L increases, the probability for the appearance of a chain with an anomalously high conductivity decreases. The current flow through a structure becomes determined by the set of the lowest-resistance chains among those present in the sample; the charge transport becomes a multichain (quasi-3D) process. The overall conductivity of a sample is the sum of the reciprocals of the resistances of the chains. The decay of the histogram at high conductivities in a-Si with $L = 440$ Å (Fig. 3b) is thus smoother than that in the 1D case (Fig. 3a).

For a quantitative comparison between the experimental histograms of the distribution of the logarithm of the conductivity and theoretical predictions, it is convenient to use the parameter ν introduced in Ref. 13:

$$\nu = 2\ln(S/La)/Q_0, \tag{5}$$

where $Q_0 = |\ln(\sigma_\infty/\sigma_0)|$ is given by (3). The physical meaning of the parameter ν is as follows. For values $\nu < 1$, there are no optimum chains in the sample. The number of chains determining the conductivity of the sample thus fluctuates from sample to sample, so there is a wide scatter in the conductivities of the various samples. At values

$$1-\nu > Q_0^{-1/2} \tag{6}$$

the conductivity of the set of samples should be described by the distribution function[13,14]

$$f(\ln\sigma) = \frac{\exp(-\Delta)}{\pi}\int_0^\infty dx\,\exp\left(-x^{\nu^2}\cos\frac{\pi\nu^2}{2}\right)$$
$$\times\cos\left(x\exp(-\Delta) - x^{\nu^2}\sin\frac{\pi\nu^2}{2}\right), \tag{7}$$

where $\Delta = \ln(\sigma/\sigma_s)$, and σ_s is given by

$$\ln\left(\frac{\sigma_s}{\sigma_0}\right) = \frac{1}{2}\left(\nu + \frac{1}{\nu}\right)\ln\left(\frac{\sigma_\infty}{\sigma_0}\right). \tag{8}$$

Figure 3a shows a plot of function (7) (the smooth curve) for $L = 330$ Å and $S = 8\times 8\ \mu\mathrm{m}^2$. The adjustable parameters here are the pre-exponential factor σ_0 and the density of states g. A good agreement between the theoretical curve and the experimental histogram was obtained for $g = 0.71\times 10^{19}\ \mathrm{eV^{-1}\cdot cm^{-3}}$ and $\ln\sigma_0 = 41.2$. Here we have $\nu = 0.69$, $\lambda = 2.4$, and $Q_0^{-1/2} = 0.15$. It is easy to see that condition (6) holds. For a structure with $L = 440$ Å and $S = 8\times 8\ \mu\mathrm{m}^2$ we have $\nu = 0.84$, $\lambda = 1.15$, and $Q_0^{-1/2} = 0.18$; i.e., inequality (6) is violated. In this case the expression for the distribution function becomes[14]

$$f(\ln\sigma) = \frac{1}{\pi w}\int_0^\infty dx\,\exp\left(-\frac{\pi x}{2}\right)\cos\left(x\frac{\Delta_1}{w} - x\ln x\right), \tag{9}$$

where

$$\Delta_1 = -\ln\frac{\sigma}{\sigma_0} - Q_0 + \ln\left\{\left(\frac{\pi Q_0}{2}\right)^{1/2}\Phi\left[\left(\frac{Q_0}{2}\right)^{1/2}(1-\nu)\right]\right\}, \tag{10}$$

$$w = \left\{\left(\frac{\pi Q_0}{2}\right)^{1/2}\exp\left[\frac{Q_0}{2}(1-\nu)^2\right]\Phi\left[\left(\frac{Q_0}{2}\right)^{1/2}(1-\nu)\right]\right\}^{-1}, \tag{11}$$

$$\Phi(y) = \pi^{-1/2}\int_y^\infty dz\,\exp(-z^2). \tag{12}$$

Figure 3b shows a plot of (9) for the values $g = 0.66\cdot 10^{19}\ \mathrm{eV^{-1}\cdot cm^{-3}}$ and $\ln\sigma_0 = 24.5$ of the adjustable parameters. We see that the theoretical curve gives a good description of the experimental results. The fact that the density of states found from an analysis of the statistics of the mesoscopic fluctuations of the hopping conductivity of thin layers of a-Si ($g \approx 0.7\times 10^{19}\ \mathrm{eV^{-1}\cdot cm^{-3}}$) is smaller than the density of states of the bulk material [$g \approx (2\text{–}3)\times 10^{19}$ $\mathrm{eV^{-1}\cdot cm^{-3}}$; Ref. 12][1)] by a factor of 3 or 4 is not surprising. A decrease in the concentration of ruptured bonds, which gives rise to deep levels in the a-Si mobility gap, was observed in Ref. 15 when ion-bombarded a-Si thin films were heated to 400 °C.

If the probability for the formation of a conducting chain is a strong function of the thickness, the inhomogeneity of the a-Si layer may contribute to the variation in the conductivities of the samples. Fluctuations in the thickness of an amorphous layer over the platelet may be caused by two factors. The first is the nonuniformity of the ion beam. In the present experiments this variability was on the order of 1%. Second, as a result of amorphization of the material by formed by an absolutely uniform ion beam is not an absolutely smooth amorphous/crystalline interface but a rough one. There have been several studies of the roughness of a-Si/Si interfaces formed by bombardment followed by heat treatment (e.g., Refs. 16 and 17). The typical linear dimension of this roughness under bombardment conditions similar to our own is less than 100 Å. One sample with an area of $8\times 8\ \mu m^2$ contains more than 10^6 fluctuations in thickness, so the effect of the roughness on the conductivity of the various samples is averaged over a large number of fluctuations in thickness. It should not lead to a scatter in the conductivities of the various samples.

4. TEMPERATURE AND FIELD DEPENDENCE OF THE HOPPING CONDUCTIVITY

Measurements of the $\sigma(T)$ dependence showed that the conductivity of the a-Si thin films obeys an activation law (curves *2–5* in Fig. 2). In contrast with the 3D case (curve *1*), however, the temperature dependence of the conductivity does not obey the simple Mott formula in (1). In samples with low conductivity (curves *2* and *3* in Fig. 2) we observe oscillations on the $\sigma(T)$ curve. As the temperature is lowered, the temperature dependence of the hopping conductivity strengthens in some places and weakens in others. The $\sigma(T)$ curve can be approximated well by Eq. (1) in each region between changes in slope. Random fluctuations in the conductivity of small-area ($S<S_0$) amorphous films when the temperature varies were predicted in Ref. 7. To the best of our knowledge, this effect has not previously been seen experimentally. The reason for the fluctuating $\sigma(T)$ is that there are changes in the realizations of the leading defect chains as the temperature is lowered.

According to Ref. 13, interchain switches can occur between chains which have either the same or different numbers of links (N). In the former case, the oscillation period is $\tau_1 = T/N$, and in the latter case it is $\tau_2 = T/N^{1/2}$. The number of resistances in one chain is given by[6]

$$N=(2L/a\lambda)^{1/2}. \tag{13}$$

With $L = 330$ Å, $a = 3$ Å, and $\lambda = 2.4$ we find $N = 9$. At $T = 300$ K we then have $\tau_1 = 33$ K and $\tau_2 = 100$ K. The temperature intervals between the two changes in slope on curves *2* and *3* in Fig. 2 are 60 and 90 K, respectively. The theoretical and experimental results thus agree well.

It can be seen in Fig. 2 that in samples with a high conductivity the fluctuations in $\sigma(T)$ disappear (curves *4* and *5*). The current flow through the sample in these cases is apparently determined by optimum chains. It follows from (3) that in this case the activation energy for the conductivity is given by

$$W=d\ln\sigma/d(1/T)=NT. \tag{14}$$

Let us compare the theoretical predictions with the experimental results for two temperatures, $T = 300$ and 77 K. Analysis of curve *5* yields $W(T = 300\text{ K}) = 320$ meV and $W(T = 77\text{ K}) = 53$ meV. From (13) and (14) we find $W(T = 300\text{ K}) = 230$ meV and $W(T = 77\text{ K}) = 46$ meV, in fair agreement with the experimental data.

We turn now to the current-voltage characteristics of the a-Si thin films. An observation of oscillations in the differential hopping conductivity $G = dI/dV$ when the voltage V applied to a short (2-μm) electron channel of a GaAs field-effect transistor varies has been reported by Orlov and Savchenko.[18] They believed that a redistribution of the voltage among the resistances of a leading chain was one possible explanation. As was shown above, the current flow in a-Si films with a thickness $L = 330$ Å and $S = 8\times 8\ \mu m^2$ is obviously one-dimensional. The conductivity fluctuations associated with a change in voltage should therefore be observed in our case also. Figure 4 shows the typical experimental V dependence of G, at $T = 57$ K for an a-Si film ($L = 330$ Å), for both polarities of the applied voltage. These curves are asymmetric with respect to the sign of the applied voltage: $G(V)\neq G(-V)$. The nature of the asymmetry varies from sample to sample, with $G(V) > G(-V)$ in some cases and $G(V) < G(-V)$ in others. This behavior of the current-voltage characteristic is typical of a mesoscopic sample.[4]

Oscillations are observed on the plot of $G(V)$; the typical oscillation period at $T = 57$ K is $\Delta V = 40$–60 mV.

The distance between the $(n-1)$-st and nth structural features was calculated in Ref. 18 for the case in which all the resistances of the chain are "soft":

$$\Delta V_{n,n-1} = \frac{kT}{e}\Delta\xi n, \quad \Delta\xi\approx 1. \tag{15}$$

Whether a hop is "soft" or "hard" depends on the relative arrangement of levels in energy space. In the terminology of Ref. 18, the resistance corresponding to a hop accompanied by the emission of a phonon is "soft," while one corresponding to a hop accompanied by the absorption of a phonon is "hard." Taking $T = 57$ K and $n = 1$, we find $\Delta V = 5$ mV from (15). This result is much lower than the experimental value.

Let us attempt to determine the oscillation period for a chain of hard resistances. According to Ref. 19, the current-voltage characteristic of one hard hop can be written

$$I_{ij}=\Gamma_0\exp(-\xi_{ij}+eFR_{ij}/kT), \tag{16}$$

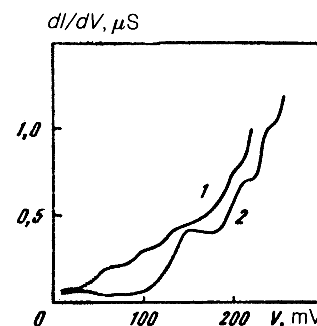

FIG. 4. Differential conductivity versus the voltage applied to an a-Si film with $L = 330$ Å at $T = 57$ K. *1*—A negative voltage with respect to ground is applied; *2*—positive voltage with respect to ground.

where $F = V/L$ is the electric field, R_{ij} is the length of the hop, and the quantity ξ_{ij} characterizes the scatter in the resistances r_{ij} in the chain: $r_{ij} = r_0 \exp \xi_{ij}$. In a shunting chain, the distances between neighboring links are equal, so we would have $R_{ij} = R = L/N$. The current-voltage characteristic of the nth hop is thus

$$I = \Gamma_0 \exp(-\xi_n + eV_n/NkT). \tag{17}$$

From (17) we easily find the oscillation period to be

$$\Delta V_{n,n-1} = \frac{kT}{e} N \Delta \xi n. \tag{18}$$

With $T = 57$ K, $\Delta\xi \approx 1$, and $n \approx 1$ we find $\Delta V = 30$ mV.

Our experimental data can thus be explained well in terms of a redistribution of voltage among the hard resistances of the leading chain.

5. CONCLUSION

The results of this study can be summarized in the conclusion that the current flow in small-area thin films of amorphous silicon can be described well by a picture of 1D chains of defects which shunt a percolation cluster. When the model of an amorphous thin film[5] is invoked to analyze the experimental results on the width of the conductivity distribution among the various samples and on the period of the fluctuations in the conductivity as the temperature and the applied voltage are varied, one finds a quantitative as well as qualitative agreement between theory and experiment.

We wish to thank V. P. Popov for measuring the backscattering spectra.

[1)] Analysis of curve 1 in Fig. 2 with the help of the Mott formula (1) yields the value $g = 3 \cdot 10^{19}$ $eV^{-1} \cdot cm^{-3}$.

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