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1994 J. Phys.: Condens. Matter 6 2583

(http://iopscience.iop.org/0953-8984/6/13/016)

J. Phys.: Condens. Matter 6 (1994) 2583–2594. Printed in the UK

Hopping conduction and resonant tunnelling in amorphous silicon microstructures

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Received 14 June 1993, in final form 26 November 1993

Abstract. The temperature dependence of hopping conduction through a one-dimensional chain of localized states has been studied in small-area ($S = 2\ \mu m \times 2\ \mu m$) thin ($L = 280$ Å) amorphous silicon layers. If the average number (N) of states in the chain is less than five, then the conductivity was observed to obey not an exponential but a power law. From these data the values of N have been extracted in a set of microstructures. It was found that chains with different numbers of states are realized in different devices. Chain reorganization with variation in the temperature has been studied. At low temperatures ($T < 40$–60 K), resonant tunnelling through localized states was observed. It was shown that the electronic spectrum of microstructures can be affected by external parameters: the electric field, temperature and light illumination.

1. Introduction

Recent investigations of charge transport in disordered microstructures with variable-range hopping (VRH) conduction [1–6] have allowed a number of novel mesoscopic effects to be observed. The origin of these effects is not connected with the existence of the phase coherence length, as it takes place in metallic samples, but is due to the existence of a characteristic length scale of percolation clusters responsible for VRH in a macroscopic disordered system [4]. Previous studies of transverse VRH conductivity in microstructures fabricated on small-area ($8\ \mu m \times 8\ \mu m$) thin ($L = 330$–440 Å) amorphous silicon (a-Si) layers (figure 1) have shown that the room-temperature conductivity fluctuates by up to 100% from one device to another and with change in the external parameters (e.g. applied voltage or temperature) [5].

The explanation of conductivity fluctuations was based on the fact that the sample conductance is dominated by a small-area but anomalously high-conduction region (a 'puncture'). This 'puncture' forms in the region of very strong fluctuations in the localized-state concentration [7, 8] and represents a one-dimensional chain of defects located at anomalously close distances to one another. Owing to the exponential spread of resistances associated with the different chains, even in a macroscopic sample only a limited number of channels (about 1) will carry the main part of the current. In large-area samples the conductance is determined by so-called 'optimal' chains, i.e. chains for which the product of their conductance and probability of formation is maximum. If the device area is so small that the average number of optimal 'punctures' over its area is less than unity, then the different chains, the number of which is about unity, will be responsible for the conductivities of different samples. In this case the configuration of a 'leading' chain, and therefore its conductivity, fluctuates strongly from one sample to another.

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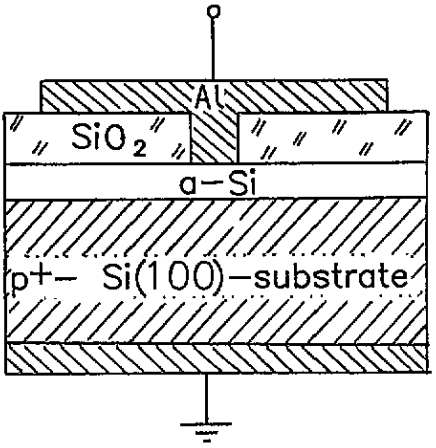

Figure 1. Schematic cross section of test microstructure.

In [6], we have reported the observation of another mesoscopic effect on a-Si microstructures: two-level spontaneous switchings in the hopping current (random telegraph signal (RTS)) with a magnitude of 0.5–10% at $T = 300$ K. We have suggested that the most plausible explanation for this behaviour is random fluctuations in the tunnelling probability for one of the hops on the best-conducting chain of defects which are caused by spontaneous rearrangements of the atomic structure in the material.

The aim of the present paper is to study the configuration of the 'leading' chain in different microstructures and how its reorganization is affected by the external factors: the temperature, electric field and light illumination.

2. Experimental details

The measurements were carried out on a series of a-Si microstructures fabricated by ion implantation on the (100) surface of crystalline silicon doped to a level of about 1×10^{19} acceptors cm^{-3} (figure 1). The thickness L of the a-Si layer was about 280 Å. It was controlled by Rutherford backscattering spectrometry and capacitance measurements at 1 MHz. The discrepancy in L obtained by different methods does not exceed 10%. The area of the top ohmic Al contact was $S = 2\ \mu m \times 2\ \mu m$.

The preparation details have been presented in [5, 6]. The sample resistance measurements were made at a bias voltage $V = 5$–12 mV. The current derivative dI/dV was measured with a standard lock-in technique at a modulation amplitude of 0.4 mV and a frequency of 11–178 Hz.

3. Experimental results and discussion

3.1. Temperature dependence of the conductivity

Glazman and Matveev [9] have theoretically shown that charge transport through an amorphous layer with a thickness R of about a few hopping lengths is determined by inelastic tunnelling along chains of localized states with energies distributed within several kT. In this case, since the energy of phonons required for electron hopping is of the order

of the thermal energy, the temperature dependence of the conductivity corresponding to the chain consisting of N states is expected to obey not an exponential but a power law:

$$\sigma \propto T^{N-2/(N+1)}. \tag{1}$$

Equation (1) is valid if

$$N \leqslant (L/a)^{1/3} \tag{2}$$

where a is the localization length. The law (1) has been observed in a Si-based MOSFET [4]. Thus, revealing law (1) by experiment, one can determine the number of localized states in a 'leading' chain. Let us estimate the value $\langle N \rangle$, averaged over our samples at $T = 300$ K. A rough estimate can be made from the obvious equation

$$\langle N \rangle = \frac{L}{R} - 1 \tag{3}$$

where [10]

$$R \simeq \frac{a}{2}\left(\frac{16}{kTga^3}\right)^{1/4} \tag{4}$$

and g is the density of localized states near Fermi level in a-Si. For $T = 300$ K, $a = 3$ Å [11], $g \simeq 0.79 \times 10^{19}$ eV^{-1} cm^{-3} [5], equations (4) and (3) yield $\langle N \rangle = 4.91$. An exact expression for the number of hops in a mesoscopic chain was obtained in [8, 12]:

$$\langle N \rangle = \lambda^{-1} \ln\left(\frac{S}{La}\right) - 1 \tag{5}$$

where the parameter λ satisfies the transcendental equation

$$\lambda = \ln\left(\frac{0.27\lambda}{kTaL^2}\right). \tag{6}$$

For $S = 2\ \mu\text{m} \times 2\ \mu\text{m}$ we find that $\langle N \rangle = 3.76$. It is easy to demonstrate that condition (2) is fulfilled for the microstructures used in experiment: $(L/a)^{1/3} = 4.53 > 3.76$. It is also of interest to determine the number N_{opt} of optimal chains in these devices. According to [8, 12],

$$N_{\text{opt}} = \frac{S}{La}\exp\left[-\left(\frac{2L\lambda}{a}\right)^{1/2}\right]. \tag{7}$$

For $S = 2\ \mu\text{m} \times 2\ \mu\text{m}$, $L = 280$ Å and $T = 300$ K, equation (7) yields $N_{\text{opt}} = 4 \times 10^{-5} \ll 1$. This means that conduction proceeds via not the optimal but the most-transparent chains the number of which is of the order of unity. The estimates made above demonstrate that, in spite of the large number of defects in the a-Si microstructure, only a few localized states (about 4) participate in conduction.

Conductivity as a function of temperature on a double-logarithmic plot is displayed in figure 2 for four different samples. As expected, in most devices the conductivity acquires not an exponential but a weak power-law dependence on temperature, with the power

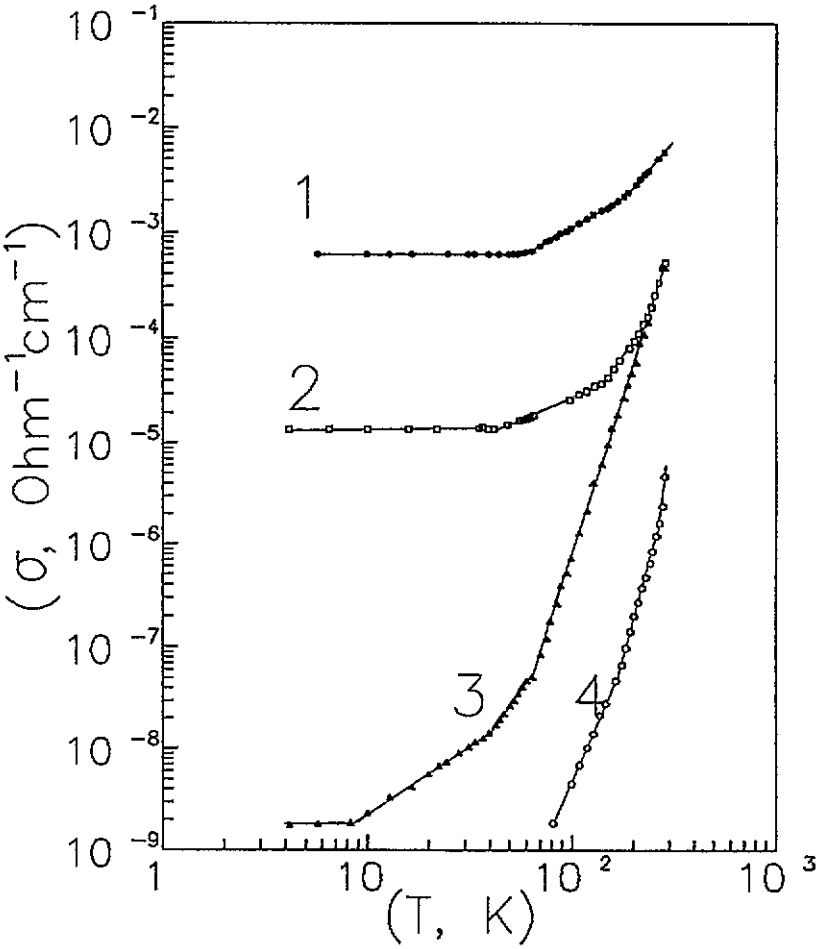

Figure 2. Temperature dependence of conductivity for four microstructures.

increasing as the temperature increases. The analysis presented in [5] of $\sigma(T)$ data shows that in microstructures with a thicker layer of a-Si ($L = 330$ Å; $S = 8\ \mu\text{m} \times 8\ \mu\text{m}$; $(L/a)^{1/3} = 4.8$; $\langle N \rangle = 6.7$) another situation has been realized; only a small fraction of devices exhibits a power-law dependence of σ on temperature. For example, curve 5 in figure 2 of [5] can be approximated by $\sigma \propto T^{3.5}$ which implies that $N = 4$. This can be understood as follows. In the chain with a large number of hops there is a very high probability that a state with energy which differs from the energy of other states by much more than kT will appear. Therefore, the process of phonon absorption with energy $W \gg kT$ wil be required in order to overcome this 'inaccessible' state. As a result, some kind of exponential-law dependence of resistivity on temperature can occur.

The least-squares fit of equation (1) to the experimental data $\sigma(T)$ allows one to determine the value of the power in different ranges of temperature, and hence the number of localized states in the 'leading' chain. The results of this procedure are shown in figure 3. The curves of $\sigma(T)$ and $N(T)$ labelled by the same number correspond to the same device. It is immediately apparent that, as has been suggested in [5], at $T = 300$ K, chains with different numbers of hops are realized in different microstructures. In our opinion, this is

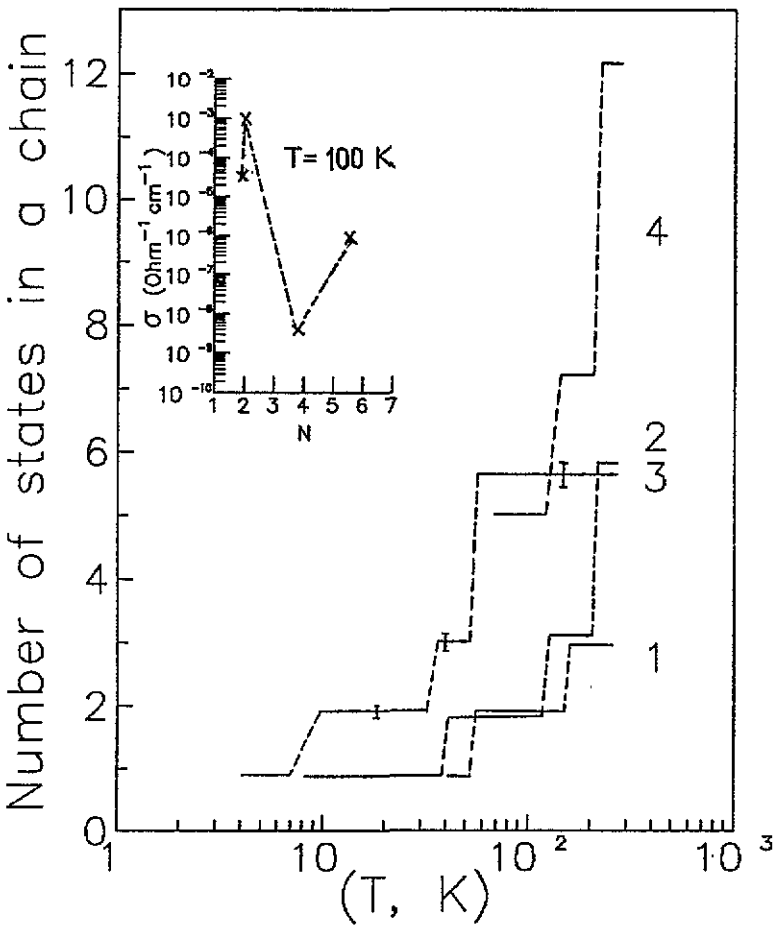

Figure 3. Number of the states in the 'leading' chain versus temperature, deduced from $\sigma(T)$ data. The $\sigma(T)$ curves (figure 2) and $N(T)$ curves labelled by the same number correspond to the same device. The inset shows the dependence of structure conductivity on N at $T = 100$ K.

the reason for the fluctuation in conductivity over the set of samples.

Since the hopping length increases as the temperature is lowered, chains with a decreasing number of states become effective. The most interesting feature of these data is the order of chain reorganization. As may be seen in figure 3, the number of states in the 'leading' chain has a step-by-step variation with temperature, and the value of the step $\Delta N \geqslant 1$. For example, N varies as $6 \rightarrow 3 \rightarrow 2 \rightarrow 1$ in device 3, and as $12 \rightarrow 7 \rightarrow 5$ in device 4. Moreover, the random character of the 'leading' chain organization leads to a random dependence of its conductance on the number of states forming the chain (see inset on figure 3).

Another problem yet to be considered is the reproducibility of the temperature dependence of conductivity. We have discovered that the dependence $\sigma(T)$ is not fully reproducible from time to time for the same device. This means that at different times a different chain is 'leading'. Such spontaneous switching of the 'leading' chain is consistent with the earlier observed effect of spontaneous fluctuation in room-temperature conductivity in a-Si microstructures and is caused by the same reasons [6]. All these facts seem to

demonstrate the mesoscopic properties of a-Si microstructures.

In some samples we have found that it is impossible to approximate the $\sigma(T)$ data by the simple law (1); the observed value of power in equation (1) proves to be temperature dependent. This result can be explained by the fact that in this case many (much greater than unity) chains with different numbers N dominate the sample conductivity.

3.2. Resonant tunnelling

As seen in figure 3, at low temperatures ($T < 40$–60 K) the chain degenerates into a channel which consists of only one localized state. In this case, conduction is expected to occur via resonant indirect tunnelling, in which an electron tunnels from one electrode onto a localized state and then in turn tunnels out to the other electrode [13] (figure 4). The resonant states are localized in the middle of the a-Si barrier ($|L/2 - x| \leqslant a$) and within several kT of the Fermi level [14]. The number of these states is given by

$$N_r \simeq gkTSa. \tag{8}$$

For $T = 4.2$ K, we find that $N_r = 0.3$. As expected, the averaged number of best-conducting channels in the resonant tunnelling regime as well as in the regime of hopping through the chains with $N > 1$ is about unity. This means that the electrical characteristics of the microcontact must reflect the concrete realization of a random spatial and energy distribution of resonant states. According to figure 2 there is a variation in low-temperature conductivity that has a spread of more than six orders of magnitude. Such behaviour may be attributed to the different spatial positions of the resonant states in different samples. Since the conductivity is strongly dependent on the tunnelling distance, the small change in state location can cause a large variation in conductivity.

The dI/dV–V curves of three microstructures at 4.2 K are shown in figure 5. The reverse-bias direction is defined as that with electrons moving from the top contact to the substrate. According to [14], in the resonant tunnelling regime the current is resonantly enhanced at biases for which the Fermi level of the electrode coincides with the energies of localized states in the barrier (figure 4). This implies that there should be a step-like structure in the I–V characteristics of microcontacts or corresponding peaks in the differential conductance. Thus the peak position of the voltage scale in figure 5 reflects the energy distribution of resonant states in a-Si. Moreover the asymmetry of the spatial positions of the states with respect to the barrier centre causes asymmetry in the I–V characteristic. The curves presented in figure 5 demonstrate that different sets of localized states are responsible for conduction in different devices.

The conductance oscillations versus applied voltage, depicted in figure 5, have been observed only at temperatures corresponding to $N = 1$. Figure 6 illustrates the effect of increasing temperature on the dI/dV–V characteristics for sample 1 (see figures 2 and 3). The curves are displaced for clarity. Oscillations disappear at $T \simeq 60$ K when a transition from $N = 1$ to $N = 2$ occurs (see figure 3). The behaviour of the peak height is in agreement with the theoretical prediction [15]; in the resonant tunnelling regime the peak height increases as the temperature is lowered owing to the diminished thermal broadening of the resonance.

Conductance oscillations versus the source–drain voltage have been observed in micron-size GaAs MESFETs [2] and a-Si microstructures [5], in which electron transport proceeds via hopping through channels that contain more than one localized state. These results were explained by a redistribution of the voltage drop among the hops within the 'leading' chain. In this model, the period of the conductance oscillations is determined by the temperature

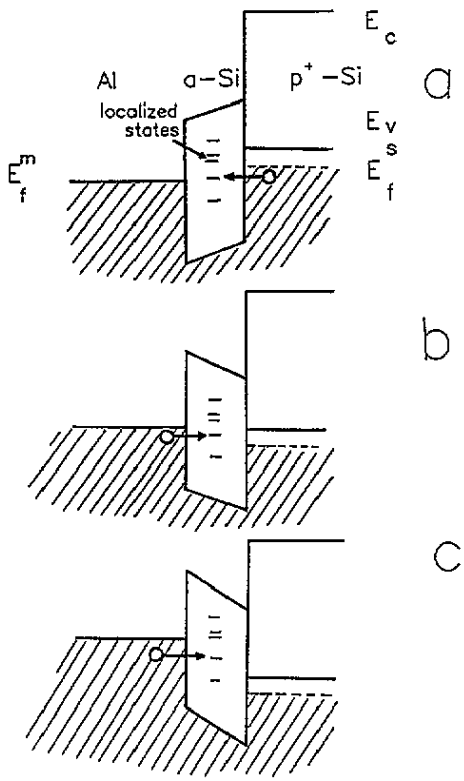

Figure 4. Schematic energy diagrams of the tunnel structure under (*a*) the forward bias and (*b*), (*c*) the reverse-bias conditions.

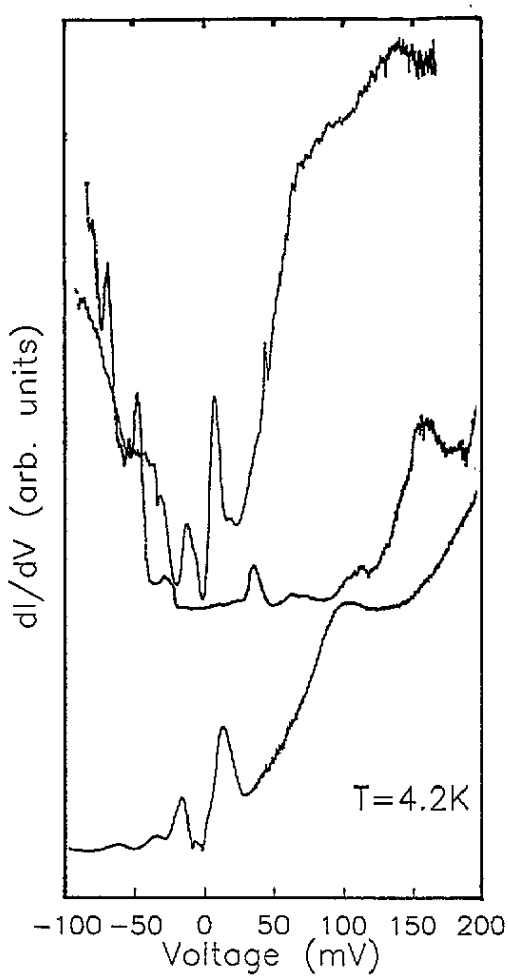

Figure 5. dI/dV curves for three microstructures at 4.2 K. The curves are shown with the axes shifted vertically.

[2, 5]. It is immediately apparent in figure 6 that conductance peaks do not change their position on variation in temperature. Thus the observed dI/dV structure is associated with resonant tunnelling.

One issue yet to be addressed is the reproducibility of tunnelling spectra. The question is whether the spectrum of differential conductance (energy spectrum of the microstructure) reflects the 'individuality' of a given sample. Detailed studies have shown that a concrete dependence of dI/dV on the applied voltage is fully reproducible in a given sample during a limited time period which at $T = 4.2$ K and an electric field $F = 1 \times 10^5$ V cm^{-1} continues from several hours to several tens of hours. Then the microstructure spontaneously switches into another state, and the conductance curve changes its form. Modification of the tunnelling spectrum proves to be caused by external factors also. Figure 7 shows the

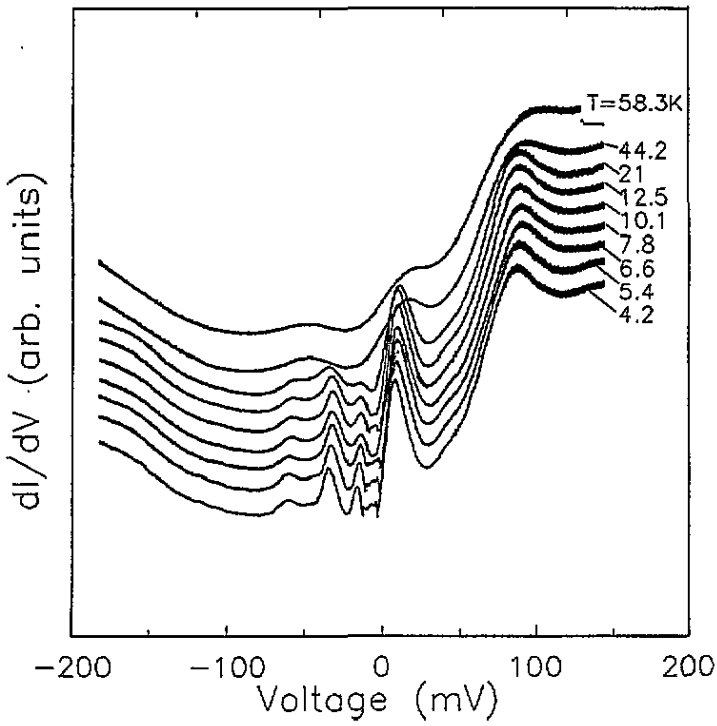

Figure 6. dI/dV curves for microstructure 1 (see figures 2 and 3) at different temperatures. The curves are shifted vertically.

conductance dI/dV versus applied voltage for the same microstructure: after cooling the sample to $T = 4.2$ K, after heating to $T = 300$ K, and cooling to 4.2 K for the first time, after heating to $T = 300$ K and cooling to 4.2 K for the second time, and after a pulse of electric field $F = 1 \times 10^6$ V cm^{-1} with a pulse duration of about 2 s.

As mentioned in the introduction, spontaneous fluctuations of hopping current in a-Si microstructures have been observed and reported in [6]. Characteristic lifetimes of the system in different conductive states have a value of about several seconds at $T = 300$ K and exponentially increase as the temperature is lowered with an activation energy of about 1 eV. This phenomenon has been explained by random rearrangements of atomic structure. Local alteration of some atomic configurations induces fluctuation in the potential and, hence, a change in the spectrum of electrons localized in potential wells. Such modification of the electronic spectrum can be detected in resonant tunnelling experiments (figure 7).

The two-level discreteness in current fluctuations allowed us to suggest [6] that a switching atomic configuration must represent the two-level system (TLS). Anderson *et al* [16] and independently Philips [17] were the first to propose the TLS to explain the properties of glassy materials. The central hypothesis of their model is that in any glass system there should be a certain number of atoms (or groups of atoms) which can be more or less equally well in two equilibrium positions. The TLS model proves to be successful in explaining the low-temperature specific heat [18], electron spin–lattice relaxation [19] and AC conductivity [20] in a-Si:H. The microscopic origin of the TLS is not yet clear. As has been suggested [19, 20], in a-Si:H the TLS may be associated with hydrogen at the dangling bonds. The H atom may flip around the Si atom, yielding two stable states. We can estimate

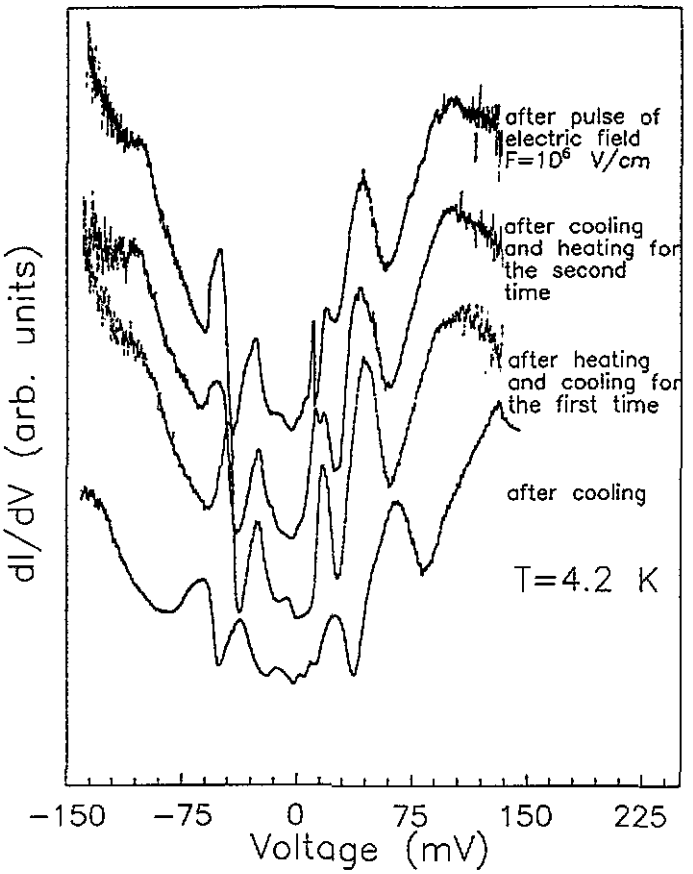

Figure 7. dI/dV curves for microstructure 2, demonstrating the influence of external parameters on the tunnelling spectrum.

the TLS concentration from the following considerations. In order for the chain conductance to exhibit two-level fluctuations it is necessary for one TLS to be located within the chain. If α is the portion of a device exhibiting RTS and ρ is the radius of the cylinder occupied by the chain, then

$$n_{\mathrm{TLS}} = \alpha(\pi\rho^2 L)^{-1}. \tag{9}$$

According to [8],

$$\rho = \frac{L}{\lambda N}. \tag{10}$$

If we take $\alpha = 0.2$ [6], n_{TLS} is calculated to be 3.6×10^{18} cm^{-3}.

The distance R_0 between sites in the TLS can be estimated using the effect of the electric field which stimulates an increase in the switching frequency. The electric field accelerates the atomic transitions; therefore a local modification of the electronic spectrum can be observed in a strong field at $T = 4.2$ K after a time as short as 1 s. Let τ_i^{-1} be the switching frequency in the electric field F_i. If we assume that dominant atomic transfer at

low temperatures is by tunnelling rather than by hopping over the barrier [16], then

$$\frac{\tau_2}{\tau_1} \simeq \exp\left(\frac{\eta e(F_1 - F_2)R_0}{kT}\right) \tag{11}$$

$$R_0 \simeq \frac{kT}{\eta e(F_1 - F_2)} \ln\left(\frac{\tau_2}{\tau_1}\right) \tag{12}$$

where ηe is the electronic charge of the flipping atom. For reasonable values of the parameters, i.e. $\eta = 0.12$ [21], $\tau_1 = 5 \times 10^4$ s, $F_1 = 1 \times 10^5$ V cm^{-1}, $\tau_2 \simeq 1$ s and $F_2 = 10^6$ V cm^{-1}, we find that $R_0 = 3.24$ Å. The values of TLS concentration and flipping distance obtained are consistent with a typical hydrogen content in non-hydrogenated a-Si and a doubled length of the Si–H bond which equals $2 \times 1.58 = 3.16$ Å [21].

We have also found that light illumination of the sample exerts a great influence on the tunnelling spectrum. Illumination was from a GaAs light-emitting diode (LED) ($\lambda = 6700$ Å) through an Al top contact about 1000 Å thick, providing passage of 10^{-5} of the overall number of photons falling on the sample. The conductance curves before and after illumination for 5 min are shown in figure 8. A new peak at $V = -100$ mV is revealed. This corresponds to the appearance of a new localized state in the mobility gap of a-Si. It is well known that deep states in a-Si are created by dangling bonds. The hopping conductivity is recognized as being directly related to these states. Therefore, the tunnelling spectrum should reflect the energy distribution of resonant states originating from dangling bonds. It seems to us that the appearance of a new peak in the dI/dV trace can be attributed to light-induced dangling-bond formation. Indeed, an increase in the dangling-bond concentration in a-Si:H after a long exposure to light has been observed by means of ESR studies [22–24].

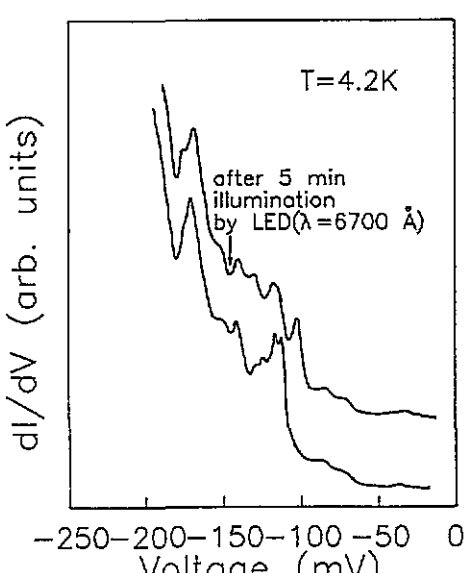

Figure 8. dI/dV curves before and after illumination by a LED.

In summary we would like to draw attention to another interesting phenomenon which has been observed in our experiments. It can be seen from figure 4(*c*) that one can expect a

sudden drop in the component of current associated with electron tunnelling from the Fermi level E_F^m of Al into the p^+-Si substrate when the bias voltage is increased beyond the point where E_F^m and the valence band edge of the substrate coincide. As a result, the total current through the structure can be seen to decrease if the field-induced increase in the current through the other resonant states located below E_F^m do not compensate the decrease in the current component through the upper resonant state (state with $E = E_F^m$). This condition can be fulfilled in devices with a small number of resonant channels and, hence, with a small value of current. The effect of negative differential resistance (NDR) has in fact been detected in some devices under the reverse-bias condition (figure 9). Moreover, the value of the current proves to be two or three orders less than in microstructures not exhibiting NDR.

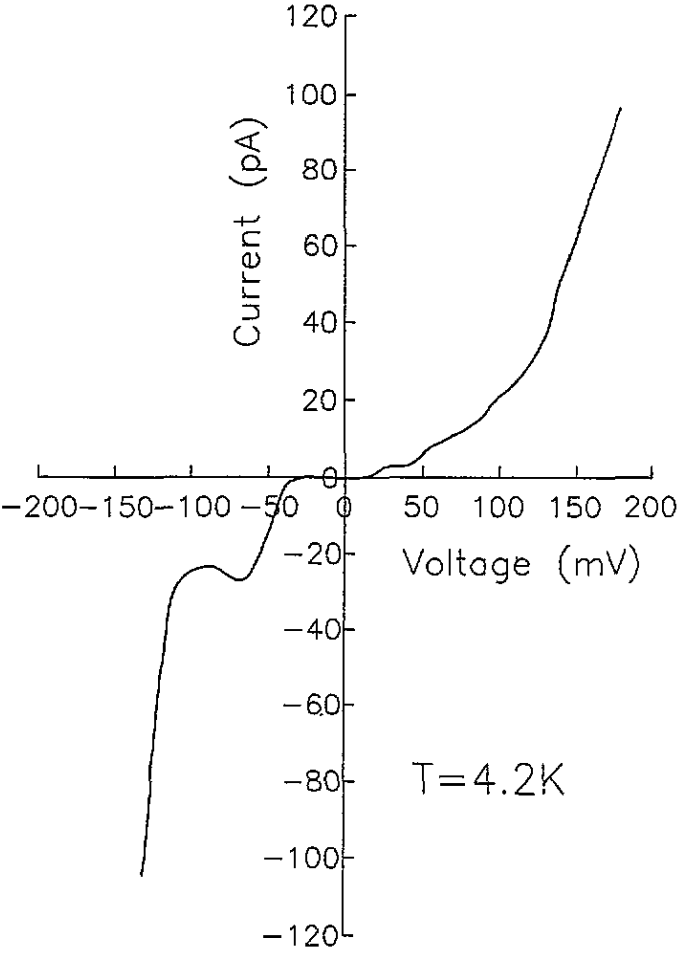

Figure 9. *I–V* characteristic of the microstructure exhibiting NDR at $T = 4.2$ K.

4. Conclusion

The total experimental data obtained in this and previous work [5, 6] demonstrate the

possibility of designing a physical object which represents a mesoscopic 1D chain of localized electrons. It is necessary to emphasize that the 'one-dimensionality' of a-Si microstructures differs from the 'one-dimensionality' of quantum wires since all the states in the chain are strongly localized, and only because of the tunnelling interaction is it possible for the electron to move in one direction.

Our results show conclusively that one cannot describe the electronic transport in small strongly localized structures in terms of specific characteristics and it is necessary to use a statistical approach.

Acknowledgments

This work is supported by the International Science Foundation (Soros Foundation). We are also grateful to Dr E Baskin for a helpful discussion.

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