Mechanism of Two-Level Hopping Current Fluctuations in Mesoscopic a-Si Based Structures

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Two-level fluctuations (random telegraph noise) of transverse hopping current have been investigated in mesoscopic nanostructures fabricated on a submicrometer area of a thin amorphous silicon layer. An electric field and light-induced change of the system lifetimes in the high and low conductive states is observed. The results are explained by formation and annealing of metastable defects in the atomic two-level hydrogen-related systems.

Introduction   A specific feature of amorphous or glassy materials is the existence of a huge number of various atomic configurations with different local minima of the potential energy. This leads to a new class of structural excitations known as two-level systems (TLS) which is characterized by low-energy transfer from one configuration to another. The TLS are thought to cause a variety of anomalies of amorphous solids. In particular, the model of hydrogen-related TLS has been successfully applied to the description of the light-induced formation of the metastable defects in a-Si:H [1,2]. Even in a macroscopic system whose characteristics should be self-averaged over the sample, one usually observes significant scatter in activation energies of defect formation or annealing [2]. When the sample size is so small that the self-averaging does not take place, one can observe the physical processes corresponding to the unit events of structural transformations in the material, which can result in a change of the electrical properties. Recently we have observed the two-level spontaneous switching (random telegraph noise, RTN) of the hopping current in amorphous silicon-based microstructures [3,4]. The aim of the present work is to establish a link between the mesoscopic fluctuations of the conductivity and the unit acts of formation and annealing of the metastable defects in a-Si based nanostructures.

Experimental Details and Results   The conductivity of structures with a thin layer of a-Si (20 nm) and small feature size 0.5×0.5 μm^2 was measured in a transverse geometry as a function of time. Details of the sample preparations have been published in [5]. The illumination was provided by a He-Ne laser (0.63 μm wavelength) with a power density of 2.5×10^{-10} W/μm^2.

Typical traces of the conductance versus time are shown in the inset of Fig. 1. To obtain the mean lifetimes of the system in high-conductive ($\bar{\tau}_h$) and low-conductive ($\bar{\tau}_l$) states, we analyzed the observed RTN either in terms of its spectral density which through the Lorentzian relationship is directly related to $\bar{\tau}_h$ and $\bar{\tau}_l$ or by statistical analysis of both times whose distribution was found to be exponential. We have established

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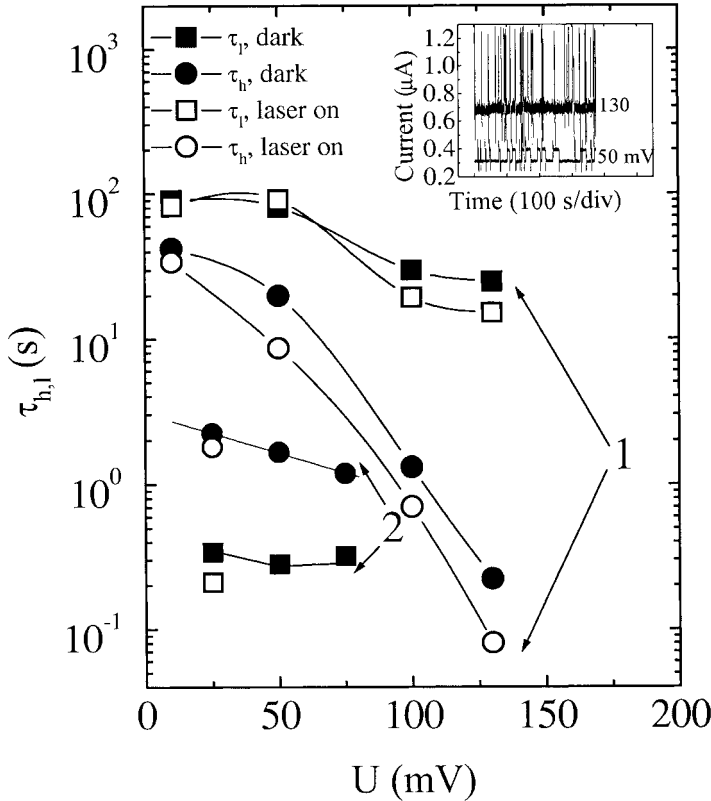
Fig. 1. $\bar{\tau}_{h,l}$ as a function of voltage for type 1 and type 2 structures. The inset shows a typical time dependence of the hopping current. The curve for 50 mV is shown with the current axis shifted up by 0.2 μA and multiplied by a factor of 3.3

that all samples can be classified into two types. Despite the fact that the magnitude of the lifetimes fluctuate by up to 100% among the samples, the samples of type 1 spend most of the time in the low-conductive state while the samples of type 2 show the opposite behaviour. In the samples of type 1, the relative magnitude of the current fluctuations decreases with applied bias and has a value as large as $\approx 70\%$. In the structures of type 2, the fluctuation amplitude is 7 to 15% independent of voltage.

Figure 1 shows the typical voltage dependence of the lifetimes in the dark and under laser illumination for both types of structures. Light illumination leads to decreasing lifetimes, the electric field F reduces $\bar{\tau}_h$ and does not affect $\bar{\tau}_l$.

Discussion The conductivity of these structures was previously described by the mesoscopic carrier transport via 1D chains of localized states. To explain the RTN signal we propose a microscopic model involving the unit atomic transitions in a hydrogen-related two-level system (TLS).

RTN in an electric field The lifetime of the metastable defect is determined by the time it takes H to come to a Si dangling bond and depends on the concentration of the hydrogen traps along its way. Since the most possible traps for migrating H in a-Si are the dan-

gling bonds D^0, the decrease of their concentration N_{D^0} should accelerate the diffusion process. The reason for the N_{D^0} change may be a modification of the charge state of dangling bonds in the electric field. This process can result from field-induced electron redistribution between deep levels by an analogy with the Frenkel-Poole effect [6]. In this case the ionization energy of the Coulomb center decreases in F, with barrier lowering being maximum for the neutral center D^0 [7]. If the electron is removed from the D^- dangling bond, the latter remains as a neutral center and F changes the probability of its ionization rather weakly. Moreover, the transfer $D^- \rightarrow D^0$ does not change the concentration of D^0 centers. As a result, some part of the electrons is transferred from D^0 centers to the states of D^- centers. The experimental decrease of $\bar{\tau}_h$ with voltage indicates that the high-conductive state results from the formation of metastable defects. This seems to be quite reasonable, because a new localized state appearing near the main hop can be included into the chain, yielding the increase of the system conductivity. The defect annealing leads to the creation of LCS. F also affects the relative value of the switching amplitude, with the effect being detected only in the type 1 structures. We believe that the two types of structures observed in this work correspond to the different configurations of the leading chain (Fig. 2). It has been found in [5] that the most conductive chain in these samples consisted of two hops, and the number of chains was about 14. If the magnitude of conductivity of one channel is changed by the order of 100%, the system conductivity has to be changed by $1/n = 7\%$. A similar value (8%) has been observed in the type 2 structures. Most likely, the TLS is located within the chain not initially inserted in the conduction (Fig. 2b). Hydrogen emission from the Si–H bond in this TLS could result in creating a new leading chain, with a resistance being comparable with the shunt chain resistance. As a result, the number of conductivity chains is changed by unity and the sample switches to the more conductive state. In this case the relative value of the fluctuation amplitude is determined by the number of chains and does not depend on voltage. The relative value of the fluctuation amplitude in the type 1 structures is $\approx 70\%$, indicating a smaller (≈ 1) number of shunt chains in the sample. The TLS is apparently situated near the states determining the main hop, and the formation of the metastable defect leads to its inclusion in the chain (Fig. 2a). Then the relative value of the fluctuation amplitude is determined by the ratio between the conductivity of a new main hop with some length r_h and the conductivity of the initial one $\frac{\Delta\sigma}{\sigma_i} = \frac{\sigma_h - \sigma_l}{\sigma_i}$. Taking into account the field dependence of the hop resistance [8], we obtain that the relative value of the fluctuating amplitude will decrease with F, $\frac{\Delta\sigma}{\sigma_i} = A \exp \frac{-eCF(r_i - r_h)}{kT} - 1$, where T is the temperature; A and C do not depend on F.
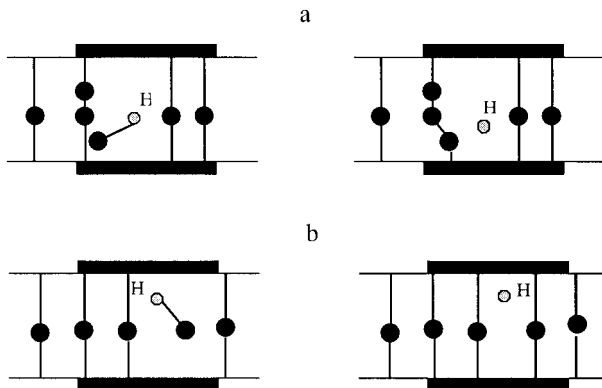
a

b

Fig. 2. Configuration of the leading chain of localized states for a) type 1 and b) type 2 structures. Right: the high-conductive state of the system, left: the low-conductive state of the system

The role of the hydrogen concentration   If $\bar{\tau}_h$ is really determined by the concentration of non-bonded dangling bonds ($N_{db} - N_H$) which are the hydrogen traps, then the larger ($N_{db} - N_H$) the larger $\bar{\tau}_h$ will be. The decrease of these bond concentration can result from the hydrogen passivation, and the local fluctuations of N_H lead to fluctuations of the dangling bond concentration and is responsible for the considerable scatter of $\bar{\tau}_h$ from sample to sample. Then the field effect should be significant in structures with a high value of $\bar{\tau}_h$. The field influence on $\bar{\tau}_h$ really proved to be more pronounced in the type 1 structures, where the $\bar{\tau}_h$ value is larger than that in the second one by a factor of 6 (Fig. 2). The fluctuations of N_H should also correlate with $\bar{\tau}_l$. The length of the weak Si–Si bond determining the activation energy of the process of metastable defect formation depends on the hydrogen presence in the nearest environment, and the activation energy (and therefore $\bar{\tau}_l$) should be smaller in a sample with larger hydrogen concentration. We indeed obtain a smaller value of $\bar{\tau}_l$ in the type 2 structures, where N_H is larger.

Light-induced conductivity fluctuations   Weakening the Si–Si bond, illumination accelerates hydrogen emission from the given bond as well as from the remote ones. When the H emitted from the remote bond is able to reach the TLS and to be embedded into a weak Si–Si bond, making it weaker, the remote "excitations" can bring an additional contribution to the decrease of $\bar{\tau}_l$. Like in the dark, the hydrogen diffusion length will be determined by the hydrogen concentration in the diffusion region and by F. In the type 1 structures the change of the switching frequency $\Delta\bar{\nu}_l$ is about 1.7 Hz (type 2 structure, $U = 25$ mV) and 0.02 Hz (type 1 structure, $U > 50$ mV). If we assume that every photon absorbed within a leading chain (radius ≈ 2.5 nm [4]) generates the hopping current switching, we should obtain an increase of the switching frequency under illumination $\Delta\bar{\tau}_l^{cal}$ by 2.5×10^{-3} Hz. To overcome the discrepancy between the experimental and calculated value we propose that H excited by a photon from the remote Si–H bond finds oneself near the leading chain in the case when the diffusion length L of H is $L = r^2\sqrt{\frac{\Delta\bar{\tau}_l^{exp}}{\Delta\bar{\tau}_l^{cal}}}$ and is ≈ 60 nm for the second structure and ≈ 6 nm for the first one at $U > 50$ mV. The difference in the diffusion lengths for the two kinds of structures is consistent with a qualitative difference in the free dangling bond concentrations resulting from the analysis of the field effect.

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