Switching in amorphous-silicon devices

M. Jafar and D. Haneman
School of Physics, University of New South Wales, P.O. Box 1 Kensington, 2033 Australia
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The phenomena of nonvolatile switching in amorphous-hydrogenated-silicon thin-film devices are explained by a theory based on the presence of charged inclusions in the film, having originated from the initial forming treatments. The inclusions almost penetrate the film, and are able to move under applied fields of sufficient magnitude, and in a direction determined by the applied polarity. The differences between analog and digital switching are ascribed to differences in the homogeneity of the inclusions, being affected by the nature of the top contact.

I. INTRODUCTION

The phenomena of switching behavior in crystalline semiconductor junction devices are well understood,[1-6] and volatile switching in amorphous semiconductor structures is also generally understood, often in terms of melting processes.[7-9] However, in cases of nonvolatile switching in amorphous materials, i.e., where the change in resistance persists after the critical applied voltage has been removed, there are still problems in providing a satisfactory explanation. In this work we propose a mechanism that could account for the phenomena in one of the most-studied cases, namely, amorphous hydrogenated Si (*a*-Si:H).

II. SWITCHING IN AMORPHOUS SILICON STRUCTURES

A typical switching characteristic for a device based on *a*-Si:H is shown in Fig. 1. Here we show our data for a 0.2-μ-thick *p*-type *a*-Si:H film deposited on a Cr-coated glass slide with a small (about 100-μm diameter) V contact on the top. The details of the *a*-Si:H deposition have been outlined previously,[10,11] the substrate temperature having been 230 °C. The device has to be subjected to a special forming treatment in which a voltage across the device is raised until the resistance is reduced (with various degrees of suddeness, depending on the device), whereafter it displays the current-voltage behavior shown. Note that "on" state resistance for this device is about 3 kΩ, whereas the "off" state resistance is about 1 MΩ. In the case of a stainless-steel-p^+-*n*-*i*-Al device, a typical characteristic is shown in Fig. 2. Here the "on" resistance is somewhat lower, at 270 Ω, while the "off" resistance ranges from 0.5 to 3 MΩ.

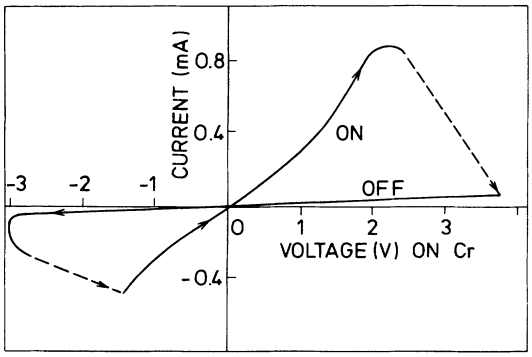

FIG. 1. A typical current-voltage curve for a Cr-p^+-V device showing the switching cycle between "on" and "off" states. The p^+ layer is 360 nm thick. The currents in the "off" state are shown exaggerated, being of order microamps. At 1.2 V, the "on" and "off" resistances are 3 kΩ and 1 MΩ, respectively. The switching changes are shown as dashed lines, covering a voltage that has a range that is a result of the use of a series resistor of several kΩ kilohm in the circuit to prevent burn-out in the "off-on" transition.

Such devices have been studied in detail over a number of years[12-19] and the theory has been addressed, but serious problems have remained. First, regenerative injection of charge carriers between junctions, as proposed for threshold switching in Si and other devices,[20] cannot be a mechanism because such regenerative effects only exist while a voltage greater than the "holding" voltage is applied. Clearly, for nonvolatile switching some semipermanent change must take place. Models based on melting phenomena[21-23] could in principle account for the "on-off" transition since the power developed is a few mW, but cannot account for the "off-on" transition,

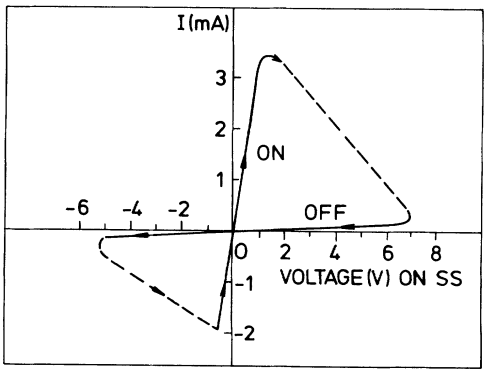

FIG. 2. Same as for Fig. 1, but for a stainless-steel-p^+-*n*-*i*-Al device. Here the layer thicknesses were p^+, 360 nm; *n*, 400 nm; and *i*, 300 nm. At 1 V, the on and off resistances were 270 Ω and 0.8 MΩ, respectively.

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where the power at commencement of switching is only a few μW. It has also been suggested[16] that the permanent memory may be produced in a manner similar to that in metal-insulator-semiconductor-semiconductor (MISS) structures[5] by a mechanism where the charge is trapped in deep-gap states at the insulator-semiconductor interface. However, it has been recognized[16] that the expected decay rates from such traps through tunneling and diffusion processes would limit the durability to periods that cannot be reconciled with the long experimental durabilities, which appear to be indefinite.

It has also been suggested[16] that the memory switching may be associated in the case of a-Si:H with some motion of hydrogen in the lattice. However, it has been shown in numerous trials[13,17,19] that the nature of the top metal contact has a strong effect on the switching behavior. Therefore a satisfactory theory must involve the top contact metal. It has therefore been suggested that the essential preliminary forming treatment, when the initial high resistance of the structure is broken down under a brief application of sufficient voltage, causes atoms from the top contact to enter the a-Si:H matrix, and leave metallic inclusions.[10,17]

A mechanism that was developed on this basis[17] featured islands of conducting inclusions between which tunneling occurred. According to this, the low-bias isothermal resistance of regions between the highly conducting ones could be expressed in ohms as

$$R = c\exp(d\beta^{0.5}) ,$$

where c was a constant determined by both geometric factors and the transmission probability, the quantity d was the numerical value of the average tunneling distance expressed in Å, and the quantity β was the numerical value of the average barrier height expressed in eV. Because of the exponential dependence, small changes in d such as from 50 to 57 Å, for a 1-eV barrier height, could cause a thousandfold increase in R. Likewise, a change in the barrier height from 1.0 to 1.4 eV, for d of 50 Å, could cause a similar increase. Localized heating or high-field effects were mentioned as possibly being able to cause such changes, but no details were provided.

There are a number of problems with these suggestions. A reversible change in barrier heights β is hard to understand. If there is a change in the interinclusion spacing d, the above model would require the whole chain of these inclusions to expand and contract, which, for say ten inclusions is a total movement of 70 Å and is also very difficult to visualize. Perhaps the most serious difficulty is that the model does not explain why a positive voltage switches the structure from "on" to "off," but a negative voltage is required to switch it from "off" to "on." In other words, it does not deal satisfactorily with polarity effects.

III. NEW SWITCHING MODEL

We now describe in some detail a model which could explain the various phenomena, including the observed high speeds, of switching in a-Si:H-based devices of the above kind. We assume that there are indeed metallic inclusions in the film, and have recently provided evidence for metallic penetration, in the case of a V top contact, from depth-profiling Auger-electron spectroscopy.[11] The key assumption we make is that there is a positive charge on the metallic inclusion, so that one can account for polarity effects.

During the initial and essential forming treatments, metal from the top contact enters the a-Si:H matrix, to form narrow filamentary regions, sometimes, but not necessarily, composed of segments. The penetration effect is mainly due to the high temperatures attained during the forming treatment, which we have measured as at least 1100 K.[11] We have observed that the polarity of the forming pulse is not important; pulses of either polarity can be used. This shows that the forming process operates by diffusion rather than electromigration.

A schematic diagram of the structure is shown in Fig. 3. The overall shape of the region is characteristic of diffusion, and the segments within will have sizes and shapes that depend on the metallurgical properties of the particular metal in the a-Si:H matrix. Thus the inclusions may be regarded as in some kind of channel in the a-Si:H matrix. Note that the resistance between the top and bottom contacts is now drastically altered. Any interface potential barrier at the top contact is clearly strongly degraded or destroyed, and if any such barrier remains at the bottom contact it must be of relatively low height. This is because it is reverse biased during the initial "on" state, yet the resistance is low. Then the main resistance of the structure is composed of two sections in series. The first is the metal-containing upper channel, of low resistance, and the second is the remaining a-Si:H matrix of relatively high resistance.

Immediately after forming, the length of the high-resistance path through the a-Si:H is close to zero, resulting in the observed device resistance being at its lowest value, several hundred to several thousand ohms, depending on the resistance of the inclusion region. As the negative voltage applied to the top contact increases, the electrostatic force on the positively charged inclusions, or chains of such, increases until at some critical range of values the inclusion(s) can overcome the lattice resistance and move back in their channel by a step amount, of length $\Delta 1$, so that the length of remaining a-Si:H is increased by $\Delta 1$. This extra length, to be quantified below, accounts for the switch to the high-resistance condition, as shown in the right sides of Figs. 1 and 2.

If the voltage continues to increase, the field across the

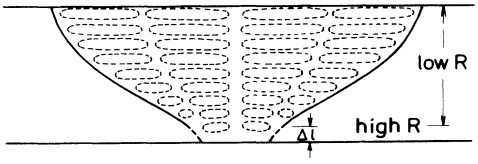

FIG. 3. Schematic diagram of charged filamentary inclusions in a-Si:H film, as a result of the forming treatment. The diagram illustrates the case of the filament being composed of separate inclusions, which appears to apply for V top contacts, but for other metal contacts a single filament may be applicable. The region $\Delta 1$ is the high resistance portion, being a-Si:H film.

a-Si:H will increase until breakdown occurs, as observed. However, if the voltage after the switching is reduced, the device will stay in the high-resistance condition, even as the voltage (on the top contact) turns positive. At a sufficiently high positive magnitude, the electrostatic force on the positively charged inclusion(s) can overcome the lattice resistance and repel them back to their former position, hence the resistance drops to its former value, i.e., the "on" state, as shown in the left sides of Figs. 1 and 2. Once in this low-resistance condition, the whole cycle can be repeated. However, if, instead of reducing the voltage, one continues to increase it, the power dissipated will become comparatively high since the resistance is in the low condition, and thus there is enough heat to damage the device, as observed.

We now address the quantitative aspects of the above model. First, we estimate the magnitude of $\Delta 1$ that is required. This depends on the size of the inclusion(s), taken for simplicity as of roughly cylindrical shape with diameter d and cross-sectional area $A=\pi d^2/4$, as shown in Table I. Here we have assumed that the resistivity r of the remaining a-Si:H is similar to its bulk value, namely 1.6×10^4 Ω cm, and have calculated $\Delta 1$ from the expression $A\Delta R/r$, where ΔR is the change in resistance, taken as 1 MΩ. As seen from Table I, the drop in resistance from about a MΩ to a much smaller value clearly requires only a small value for the expansion $\Delta 1$. This small value is also consistent with the short switching times involved, illustrated in Fig. 4. The "on"-state resistance is now that due to the metallic inclusions plus that of the remaining a-Si:H path, but the latter path must clearly be negligible if its resistance is to be only about 1 kΩ. One could demur about the condition in the "on" state, that the inclusions penetrate nearly all the a-Si:H matrix. However, experimentally the forming process is indeed critical. It is most important to stop the applied voltage immediately after the current starts to rise, otherwise the device is destroyed. This is consistent with the above requirement of near-total penetration.

The next question is the magnitude of the supposed charge on the inclusion(s). For an electromigration effect, assume that the charge on an inclusion is q, and the force F due to an electric field E is qE. The maximum allowable value of E is about 10^8 Vm^{-1}. Having regard to the observed switching times of tens of ns or less (see Fig. 4), we assume that an inclusion portion of cylindrical shape and mass m moves 10 Å in 10 ns, which is an acceleration of 2×10^7 ms^{-2}. Then $q/m=a/E=0.2$ C kg^{-1}. If we take q as one electron charge, we obtain $m=0.8\times10^{18}$ kg. For a filament of diameter 0.2μ, which is the kind of dimension already deduced,[16] and a vanadium density of 5.6×10^3 k gm^{-3}, this translates to a length of 50 Å. The figures appear to be reasonable, even if only one charge is assumed for an inclusion portion. If there is only one elongated inclusion, the total charge would be proportionately more, i.e., one electron charge per 50 Å of length.

TABLE I. Dependence of the quantity $\Delta 1$, the distance moved by the filamentary inclusion during switching, on the assumed diameter d for the filament. A change of resistance of 1 MΩ is assumed.

d (nm)	500	400	300	200	100
$\Delta 1$ (nm)	1.23	0.79	0.44	0.2	0.03

The physical question is how the inclusion(s) can retain a charge without it leaking away. The situation probably has its origin in the presence of interface states at the inclusion–a-Si:H boundary. Such metal–a-Si:H boundaries usually result in band bending in the a-Si:H, attesting to the presence of a dipole layer at the interface. In the case of a small metallic inclusion, there are boundaries on all sides, hence there is a ready possibility for charge to be trapped on the inclusion(s). Clearly there can be no metallic contact between the inclusion(s) and the top contact.

The question arises as to why the sign of the charge is positive. In our experience, the switching characteristics of very many devices formed using p-type a-Si:H are always of the type shown in Fig. 1. Therefore there is some systematic factor that results in trapping of positive charge, independently of the nature of the top metal. The effect of a positive charge on the metal at the interface with the a-Si:H is to attract electrons from the a-Si:H to the interface, causing the bands in the semiconductor to turn "down," which is consistent with the usual

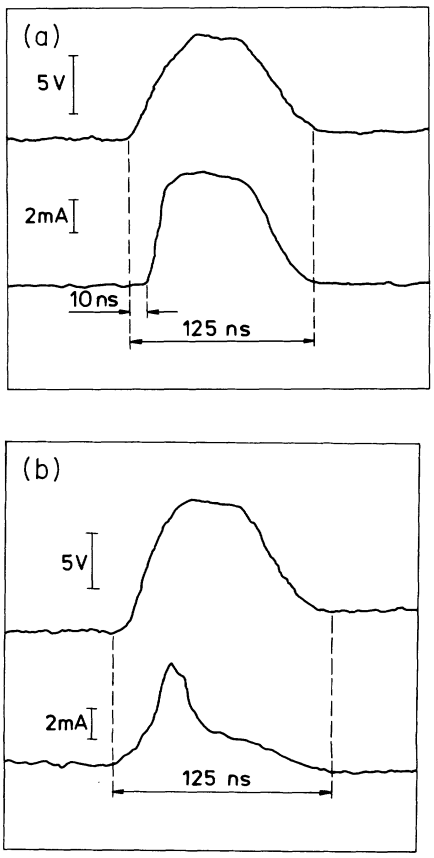

FIG. 4. Plots vs time of applied voltage pulse (top curves) and induced current pulse (bottom curves) for voltages sufficient to cause switching in Cr-p^+-Ag device. (a) "off-on" transition. (b) "on-off" transition.

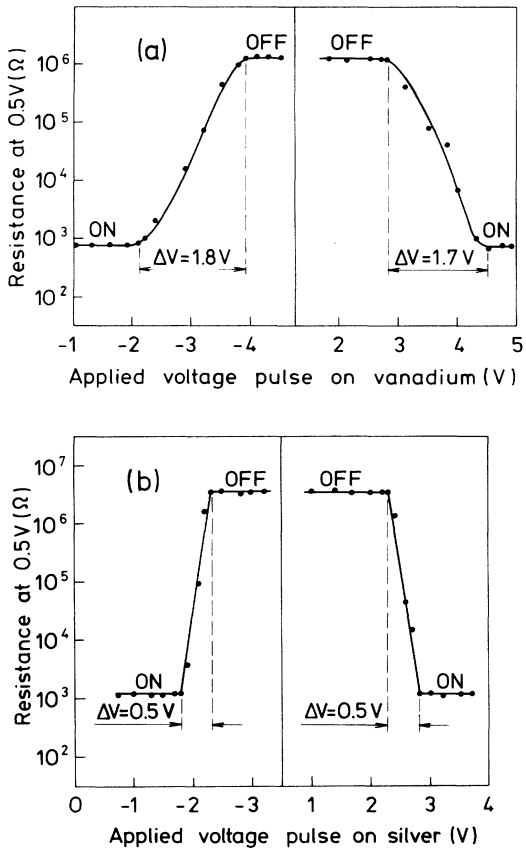

FIG. 5. (a) Plot of resistance, measured at 0.5 V, for a Cr-p^+-V device after application of a series of successively increasing 0.5-ms rectangular voltage pulses. Note the significant voltage range, which is so-called analog behavior. (b) Same as (a), for a Cr-p^+-Ag device. Note the smaller voltage range, called digital behavior.

case of p-type a-Si:H in contact with metals.

With the aid of the model, we are now in a position to consider three further phenomena. It is noted from Figs. 1 and 2 that the p^+-n-i device has a lower "on"-state resistance than the p^+ device. This difference appears to occur for these devices in general, the values for the former being in the range 100–500 Ω and for the latter in the range 1–5 kΩ. We now can relate this difference to the difference in their forming characteristics.

The p^+-n-i devices undergo a so-called "hard" forming, in which the forming takes place suddenly at high voltages (30–35 V) and over a very narrow forming range (less than 5 V). This makes control more difficult, and would lead to a greater amount of metal penetration, giving a lower resistance. On the other hand, p^+ devices exhibit "soft" forming, where the change from the unformed to formed conditions is more gradual, allowing better control during forming. The device forms between 10 and 15 V. Hence the metal penetration can be less.

Another phenomenon of interest is that certain devices exhibit so-called "analog" switching, in which the change from the "on" to "off" conditions, and vice versa, occurs in a relatively large voltage range of about 1.8 V. In some other devices, the switching is "digital," in which the changeover occurs in a range of about 0.5 V. The characteristics are shown in Fig. 5. The difference appears to be related entirely to the composition of the top contact. Thus for otherwise identical p^+ a-Si:H layers on Cr substrates, devices with top contacts of V, W, Ni, or Co, show analog switching, whereas ones with Cr and Ag show digital switching.[17] We explain this by proposing that the inclusions have an irregular front profile in the case of the analog metals, but a more uniform one in the case of the digital metals. In the former case, the change in resistance will occur over a range of voltages until the thin remaining a-Si:H layer is substantially freed from inclusions ("off" condition) or almost fully penetrated by the majority of the inclusion front ("on" condition).

With regard to switching times, it may be noted that there appears to be a small delay of 10 ns in the "off-on" transition, Fig. 4(a). This is due to the time for the voltage to reach a magnitude necessary to cause the "off-on" transition. There is no corresponding effect in the reverse transition because the resistance is low and the current follows the voltage.

IV. CONCLUSION

In summary, the overall picture is that during the forming treatment, the top small contact becomes significantly heated, resulting in metal diffusing into the a-Si:H matrix, creating inclusions. In the case of vanadium, the metallurgical properties are such as to form small chains of inclusions, hence leading to quantum effects as explained earlier.[10] In the cases of other metals, the chains may still occur, or alternatively an elongated single inclusion. For some metals the inclusion front is significantly more irregular than for others (leading to analog rather than digital devices). The metal-semiconductor interface equilibration results in a positive charge on the inclusion(s), which form some kind of channel in the a-Si:H matrix, allowing small physical motion in the channel under the application of electric fields. The model appears to provide an explanation for a range of observed phenomena.

ACKNOWLEDGMENT

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