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Resistance Switching Characteristics in Polycrystalline Silicon Film Resistors

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ABSTRACT

Both reversible and irreversible resistance switchings have been investigated in boron- and arsenic-doped LPCVD polycrystalline silicon film resistors. The effects of film thickness and doping concentration on the transition voltage and current have been characterized for different length resistors having film thickness from 0.1 to 1.2 μm and doping concentration ranging from 5×10^{16} to 1×10^{20} cm^{-3}. Under a large voltage bias, the resistor can be switched to a conductive "on" state or to a "short" state having resistance reduction by a factor of 10^3-10^6, or it can be blown "open". The transition voltage and current and the resistance after switching depend strongly on film thickness, doping concentration, and applied power. A simple qualitative model is proposed to explain these resistance switching phenomena.

Polycrystalline silicon (polysilicon) films have been widely used as solar cell and integrated-circuit elements, and such applications have stimulated extensive studies of the electrical properties of this material. Both reversible and irreversible resistance switching phenomena have been reported (1-3). The irreversible resistance switching has been extensively applied to integrated-circuit applications, such as a memory element in fusible-link PROM's (3-5) and a fuse or antifuse in redundancy circuits in high density RAM's (6). However, there are a limited number of papers in the literature systematically studying resistance switching properties of polysilicon resistors. Greve studied the programming mechanism of heavily doped polysilicon resistor fuses and showed that formation of a second-breakdown state is necessary to blow open the fuses (1). He also studied n$^+$-p-n$^+$ polysilicon devices and showed that the dopant migration and the aluminum penetration in molten filaments through polysilicon devices are the mechanisms for resistance switching (7, 8). On the other hand, Mahan reported a reversible switching phenomenon in undoped polysilicon resistors having high value resistance (2).

This work reports new experimental results on the effects of film thickness, doping concentration, and device dimensions on resistance switching behavior in polysilicon resistors. The resistances before and after switching, the switching I-V curves, and the transition voltage and current beyond which the switching occurs were characterized extensively. Different switching patterns have been clearly identified from this systematic study, and a better physical understanding of the switching behavior in polysilicon resistors has been obtained from a qualitative model.

Sample Preparation and Measurements

A 0.80 μm thick oxide was grown at 1100°C on top of N-type (100) silicon wafers with resistivity of 4 ~ 7 Ω-cm. Undoped polysilicon films with thickness ranging from 0.1 to 1.2 μm were deposited in a low pressure CVD reactor at 620°C with deposition rate of 80 Å/min. Either boron or arsenic dopants were then implanted with various doses to yield doping concentrations from 5×10^{16} to 1×10^{20} cm^{-3} for arsenic and from 5×10^{16} to 2×10^{18} cm^{-3} for boron. After polysilicon resistors were patterned by plasma etching, an 8000Å CVD oxide layer was deposited at 430°C to avoid dopant evaporation during subsequent thermal steps. For p-type samples, the contacts were either undoped or heavily doped with boron. For n-type samples, the contacts were all heavily doped with arsenic to avoid Schottky barrier formation. All samples were annealed at 900°C for 60 min to activate and uniformly redistribute the dopants, as well as to remove the implantation damage. A 1.0 μm thick aluminum layer was deposited and etched to form the contact pattern. The contacts were sintered in N$_2$ at 450°C for 20 min.

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The thickness of polysilicon films was measured by an optical method (Nanospec Model Axp-010-0180) and an α-step profiler. Measured electrical properties of polysilicon resistors include zero bias resistance and I-V characteristics. The measurement systems were: (i) an HP 4140B picoampere meter with dc programmable voltage source, coupled to an HP-85 microcomputer to measure the zero bias resistance, and (ii) a Tektronix 576 curve tracer to observe I-V characteristics and to trigger polysilicon-resistance switching. The surface of resistors after switching was studied by an optical microscope and a scanning electron microscope (SEM).

Results

The general behavior of the I-V characteristics of polysilicon resistors is illustrated in Fig. 1. The I-V curve of polysilicon resistors before switching follows the predicted hyperbolic sine function (curve 1) (9, 10) to a certain point A. It was found that the high voltage part of curve 1 was not stable for most device configurations. The resistivity drastically decreases with increasing voltage, and would contract to a stable curve 2 ("off" state) (2).

When voltage increases along curve 2, a negative resistance behavior may appear. When the voltage further increases, the I-V curves of devices of light doping concentration and short dimensions were switched to a more conductive "on" state (curve 3). When the power of the curve tracer was limited below a certain value, the negative resistance characteristic is stable and the switching between curve 2 and 3 is reversible. This reversible switching in polysilicon film was reported by Mahan as "threshold switching" (2). When more power was added into the resistor, a sudden change from "on" state (curve 3) to the "short" state (curve 4) occurred for thick film devices. However, for thin film devices, more power can cause the resistor to "open" (curve 5). Both switchings from curve 3 to 4 and from 3 to 5 are irreversible. For medium and heavily doped polysilicon resistors, the switching always jumps directly from "off" state to either "open" or "short" state without going through the "on" state. For example, in boron-doped samples with $N_A \geqslant 5 \times 10^{17}$ cm^{-3}, no switching to "on" state has been observed. However, for short and lightly doped samples ($N_A \leqslant 1 \times 10^{17}$ cm^{-3}, and nominal length less than 15 μm), reversible switching was observed.

Similar observations were made on arsenic-doped polysilicon resistors, and the same conclusions were obtained. These various switching patterns are summarized in Fig. 1. The reversible switching is more likely to occur for short and lightly doped samples. No reversible switching has been observed for our samples with doping level higher than 1×10^{17} cm^{-3} and/or longer than 15 μm.

Along the stable curve 2, the voltage beyond which the switching occurs is defined as "transition voltage," V_T, and the corresponding current as "transition current," I_T. The zero bias resistance before switching is defined as R_b and after switching as R_a.

Figure 2 shows the transition voltage and resistance *vs.* doping concentration for boron-doped resistors with lengths of 10 and 5 μm before and after switching. The resistance before switching strongly depends on the doping concentration, especially around a critical doping concentration N^* where most of the grains change from total depletion into partial depletion, thus causing a drastic change of resistance (10). An interesting phenomenon is that the transition voltage has shown a maximum around N^*. Away from N^* on the heavily doped side, the transition voltage generally follows the decreasing pattern of R_b. It was also found that the transition voltage scales proportionally to the resistor length. Resistance after switching decreases by a factor of 10^3-10^6. For the short and lightly doped samples, the resistor mostly switched first to "on", then to "open" rather than "short".

As the maximum power of the curve tracer was raised from 0.5 to 2.2W, the resistance after switching (already "short") can be further reduced by a factor of 10^2-10^4. Fi-
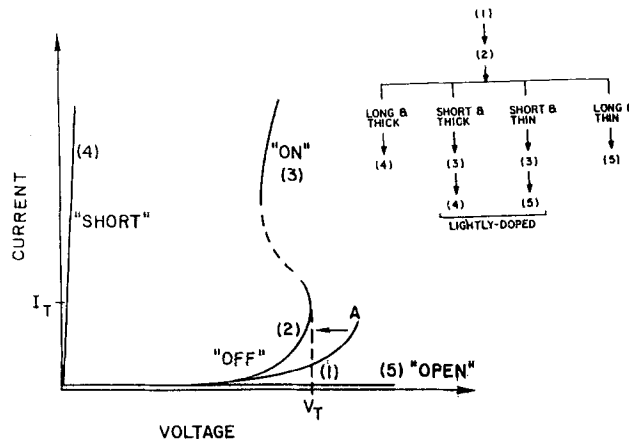

Fig. 1. The general I-V switching behavior of polysilicon resistors

nal resistance is approximately several ohms and relatively independent of doping concentration (Fig. 3). Shiny aluminum penetration path was found in these further "short" state resistors, which accounts for the low resistance.

Figure 4 shows the relationship between film thickness and measured resistances before and after switching for two doping concentrations of 1×10^{17} and 2×10^{18} cm^{-3}. The resistance before switching decreases drastically as the film thickness increases for resistors at doping concentration of 2×10^{18} cm^{-3}, but not so much for resistors at doping concentration of 1×10^{17} cm^{-3}. The details of effect of doping effect on resistivity *vs.* film thickness was investigated by Lu *et al.* (12). Almost all the devices with film thickness less than 2000Å were switched to "open" state, and R_a is infinite.

The behavior of V_T *vs.* film thickness is shown in Fig. 5. It is similar to the relationship of R_b *vs.* film thickness in Fig. 4, except that for the thinnest sample at doping level of 2×10^{18} cm^{-3}, the transition voltage decreases and the postswitching was an "open" state instead of a "short" state. The similar behavior between V_T and R_b suggests that Joule heating plays an important role in the switching mechanism (1, 2).

Figure 6 shows the V_T and I_T of boron-doped resistors at doping level of 2×10^{18} cm^{-3} for various film thicknesses. There is no significant difference whether the contacts have been heavily doped or not (12). It is found that over the observed range of film thickness, I_T and V_T obey an
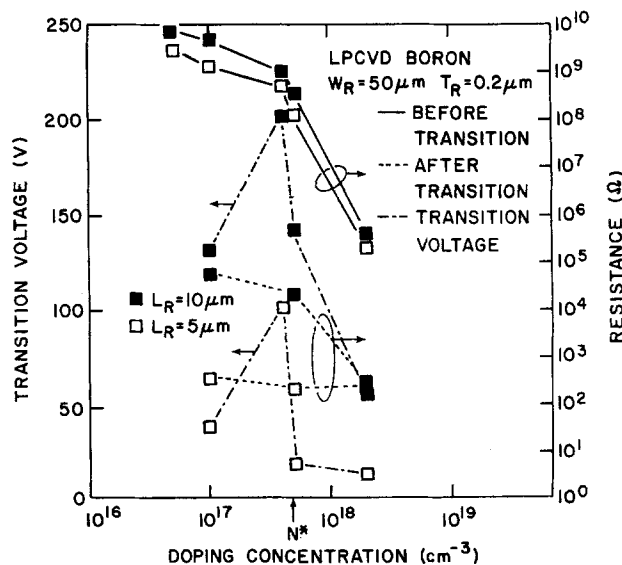

Fig. 2. Transition voltage and resistance vs. doping level before and after switching (power ≤ 0.5W).

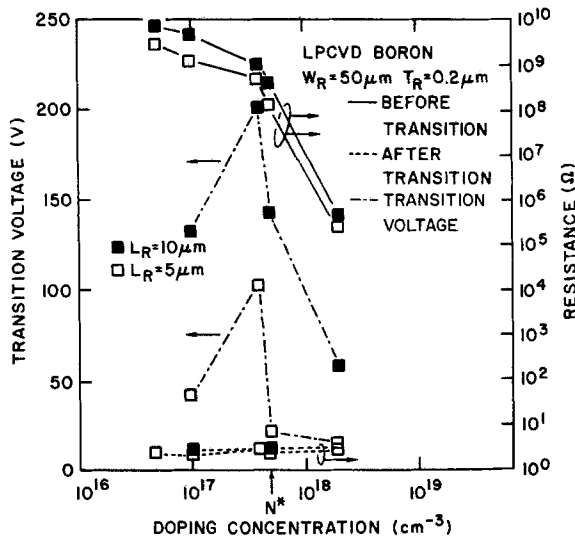Fig. 3. Transition voltage and resistance vs. doping level before and after switching (power ≤ 2.2W).

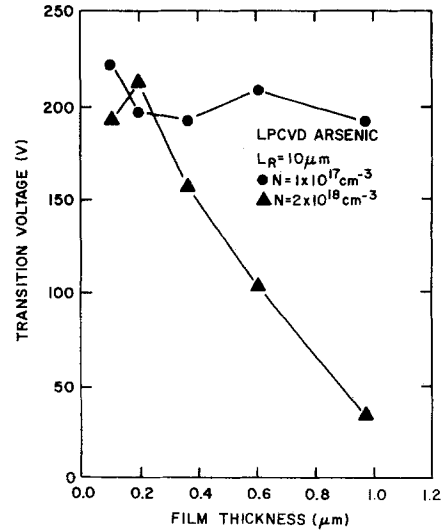Fig. 5. Transition voltage vs. film thickness

empirical expression

$$I_T = I_o[\exp (V_o/V_T)]$$

where I_o and V_o are empirical parameters.

Discussion

A simple qualitative model is proposed to understand the above observations. When the applied voltage is below the transition voltage, the I-V characteristics of polysilicon resistor can be described by the carrier trapping and dopant-segregation models (9-13). According to these models, the active dopant concentration can be obtained by subtracting the inactive segregated dopant concentration from the actual doping concentration (10, 11), and the grain-boundary trapping states can trap free carriers from the ionized active dopants and act as recombination centers (14, 15). This trapping process reduces the number of free carriers and creates built-in potential barriers surrounding the grain boundary, which impede carrier motion from one crystallite to another. The carrier transport across the grain boundary and the built-in potential barriers by thermionic emission and tunneling processes show a hyperbolic sine function I-V characteristic (13).

As the applied voltage further increases, the forward-biased space-charge barrier can eventually be flattened

and a great number of carriers is then injected into the resistors. Once this happens, bulk resistance of silicon crystallite becomes dominant, and the I-V characteristic exhibits a transition from "grain-boundary limited" to "bulk-limited" condition. Thus the observation that transition voltage reaches a maximum value around the critical doping concentration can be understood by the fact that the highest built-in potential barrier exists at this doping concentration (10) and, therefore, a higher voltage is needed to flatten the forward-biased built-in potential barrier.

For lightly doped polysilicon films, the crystallites are totally depleted by the grain-boundary trapping states, and hence the films are nearly intrinsic. The resistivity of totally depleted polysilicon films is very high, and this semi-insulating property is mainly due to carrier depletion rather than mobility degradation (10). If a finite voltage which is large enough to flatten the built-in potential barrier is applied across the resistor, a large number of electrons and holes can be injected at the cathode and the anode, respectively. Because there are more unfilled grain-boundary traps for capturing minority carriers than for majority carriers, the lifetime of minority carriers is shorter.

If the resistor is long compared to the mean free path of minority carriers, the minority carriers are not able to transverse the resistor, and this condition results in single injection. Under a high current level, majority-carrier single injection is space-charge limited (16). However, as the bias is further increased, the field across the resistor eventually becomes high enough to allow the minority
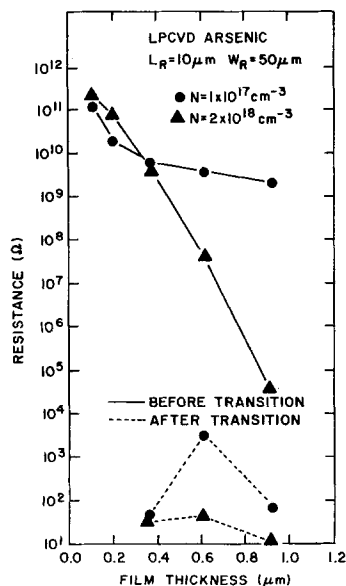

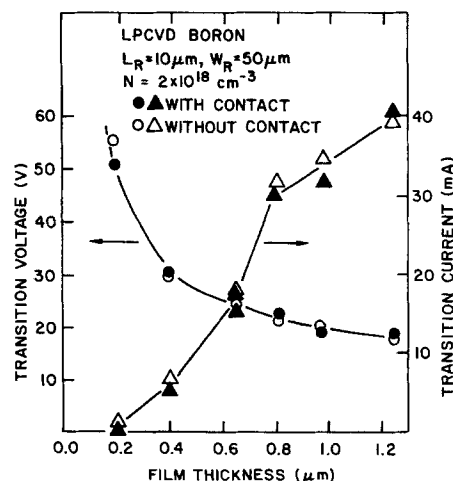Fig. 4. Resistance vs. film thickness before and after switching

Fig. 6. Transition voltage and transition current vs. film thickness

carriers to reach the other end of the resistor. This double injection process causes the majority space-charge barrier to be lowered and minority carrier lifetime (mobility) to increase, permitting more carriers to transit the resistor; as a result, a lower voltage is required to provide the current for maintaining the condition. This positive feedback process results in negative resistance characteristics. The condition causing this negative resistance behavior is that the minority carrier transit time is equal to their lifetime. It is clear that in a shorter resistor it is easier to reach this condition. Eventually, the high level injection condition will be reached when the lifetimes of minority and majority carriers are equal. At this point, two-carrier recombination-limited current flow prevails and the negative resistance behavior terminates; the polysilicon resistor can then switch to the "on" state. This double injection mode is much more likely observed for small grain and/or lightly doped polysilicon films which have plenty of recombination centers for both majority and minority carriers (17).

Similar phenomena have been observed in many amorphous semiconductors where the initiation of switching and the maintenance of the "on" state in threshold switching can be satisfactorily explained as a double injection electronic process (18, 19). Undoped or lightly doped polysilicon films of small grain size have many properties close to amorphous films. Just like any electronic transport process, heat will be generated by current, and thermal effects will accompany this electronic injection process. For short polysilicon resistors, however, the high field induced carrier generation is more likely to occur before thermal effects take over the major role. Therefore, if the double injection process and positive feedback mechanism occur before Joule heating makes any microstructure change, a reversible threshold switching occurs. However, if more power is fed into the "on" state resistor, the Joule heating will finally become large enough to cause an irreversible switching from "on" state to "short" or "open" state.

For heavily doped polysilicon films, although the grain-boundary trapping states are completely filled up with majority carriers, the concentration of free majority carriers is still substantially larger than the intrinsic carrier concentration and of the same order of magnitude as the active doping concentration (10, 11). The lifetime of minority carrier is much shorter than that of majority carrier. This majority carrier transport process is not space-charge limited. The double injection condition is hardly reached even under a relatively large bias. Usually, the thermal process will then prevail to induce current filamentation (20). Thermal current filamentation results in irreversible switching to either "short" or "open" state, depending on the configuration of resistor and programming conditions. For thick and short resistors, thermal filamentation can induce either dopant migration or aluminum penetration through the molten filament to form "short" state (1). For thin and long resistors, Joule heating can simply evaporate the polysilicon film to leave a void (21), or the applied field can be strong enough to sweep the molten silicon ions to form an "open" gap (1).

It should be noted that the coexistent electronic and thermal processes always compete and influence each other. Therefore, the device configuration, composition of the resistor, and the programming conditions all have their roles and become a control parameter in some particular stage of this complex switching phenomenon.

Conclusion

Several distinct patterns of polysilicon resistance switching have been observed for both arsenic- and boron-doped materials over a wide range of doping concentration and film thickness. The transition voltage reaches a maximum value around the critical doping concentration, which separates the totally depleted and partially depleted cases. Beyond this point, toward higher doping levels, the transition voltage generally follows the variation of R_b. As applied power increases, resistance after switching to "short" state can be further decreased and becomes less dependent on film thickness and doping level and, finally, aluminum penetration occurs, causing a resistance of only a few ohms.

Lightly doped resistors are more likely to show reversible threshold switching, probably due to their abundant recombination centers. Short and thick resistors are more likely to switch to "short" state, and the aluminum penetration path can be easily observed. Long and thin resistors are more likely to switch to "open" state, and a physical gap is observed. These distinct patterns have been understood by a qualitative model.

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