Asymmetry of the transient on-state characteristics of a threshold switching noncrystalline chalcogenide semiconductor

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Very rapid probing pulses applied to the threshold high-conductance on state of a noncrystalline chalcogenide semiconductor have shown that the transient current-voltage (I-V) characteristics for the blocked on state (TONC) need *not* be symmetrical about the origin, as previously reported. The previous work employed approximately square diagnostic pulses; in the present work the I-V characteristics of the on state are measured point by point during a very fast descending ramp of controllable slope. The results show that the symmetry or asymmetry of the TONC depend entirely on the ramp slope. When the slope exceeds a critical value, then TONC does *not* develop, and a quasilinear I-V characteristic is obtained. These observations are tentatively interpreted in terms of charge trapping and liberation.

The transient on characteristics of a noncrystalline semiconductor threshold switch (referred to as the TONC) were first reported by Prior and Henisch.[1,2] That finding, and all the measurements mentioned below, was made on thin ($\sim 1\ \mu$m) layers of a multicomponent chalcogenide alloy between electrodes of pyrolytic graphite. Such devices have been called "Ovonic threshold switches (OTS's)." They are characterized by symmetrical on and off states, differing in conductance by several orders of magnitude.[3–5]

We are here concerned not with the overall switching behavior of such systems, which is already well known, but only with the TONC as such. The TONC represents the I-V characteristics of the noncrystalline device which arise during fast electrical deformation of the on state. These deformations were imposed by the application of "rare" single and almost square diagnostic pulses, which cause the on voltage to drop to specific values (including zero) for specific time intervals.[5] Typical I-V characteristics as derived in previous studies made in this way are given in Fig. 1; method shown in the inset. It has now been found that if the I-V measurements are made *during* the descent time (which is controllable to ns precision), then the resulting I-V characteristics can be very different from those shown in Fig. 1. The voltage versus time profile for fast and slow diagnostic ramps is shown schematically in Figs. 2(a) and 2(b). During a ramp phase, the current is, of course, a function of time. Figure 3 illustrates this for a slow ramp, descending to zero voltage. There is first an almost vertical I-V region that leads in due course to the almost horizontal blocked on state. That develops when the system has spent about 75 ns below the holding voltage condition. No attempt had so far been made to investigate the symmetry of the I-V, nor to impress very fast diagnostic ramps to explore whether or not the blocked on state can be bypassed. Special care was here taken with the voltage measurement, to exclude external series resistances which could introduce errors. Freedom from unwanted capacitances and parasitic oscillations was checked by substituting parallel combinations of pure resistances and capacitances for the devices under test.

The difference between slow and fast ramps is illustrated by the results in Fig. 4. For the slow ramps (closed circles in Fig. 4), one observes a TONC having the traditional slope, but showing *asymmetry* about the origin. Many forms of this asymmetry are observed, depending on the ramp rate; the data in Fig. 4 represent only examples. The TONC becomes symmetrical under the descending ramp function only when the system is forced to spend a certain critical minimum time below the holding voltage.

For the very fast ramp rates ($\times$ data points in Fig. 4), one obtains a relatively straight-line characteristic. That state does not have as low a differential resistance as the

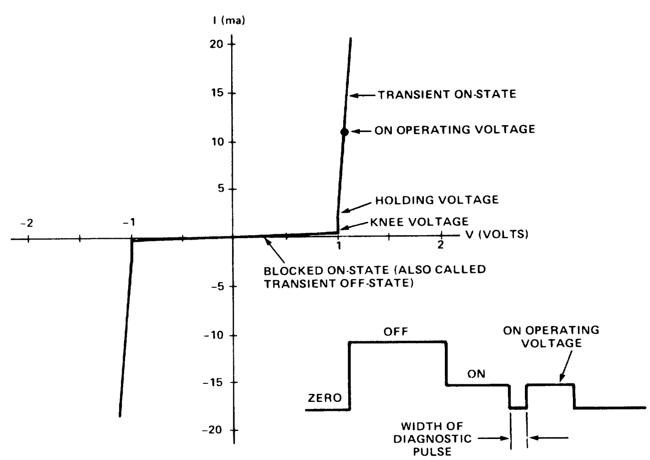

FIG. 1. The I-V for the transient on characteristics (TONC) of an OTS, as obtained by using rare square pulse interruptions (shown in the inset). The term "rare" is used to signify that the double pulses are applied infrequently to avoid any thermal effects.

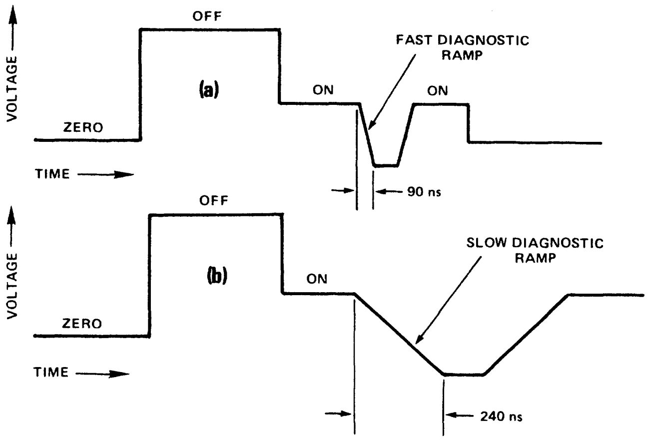

FIG. 2. Schematic of voltage versus time for fast and slow descending ramp interruption of the post-switching on-state to zero voltage and beyond.

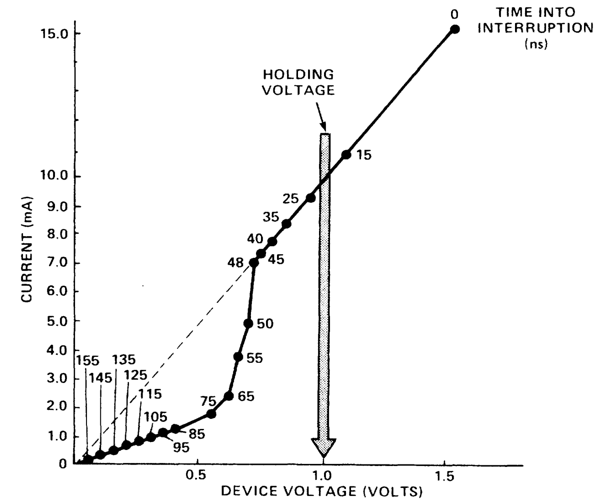

FIG. 3. Consequences of slow ramp interruptions, produced as in Fig. 2, and shown as I vs V (as a function of the time below the operating condition, which is designated zero ns). Note the development of the almost horizontal region of the TONC after critical time interval below the holding voltage.

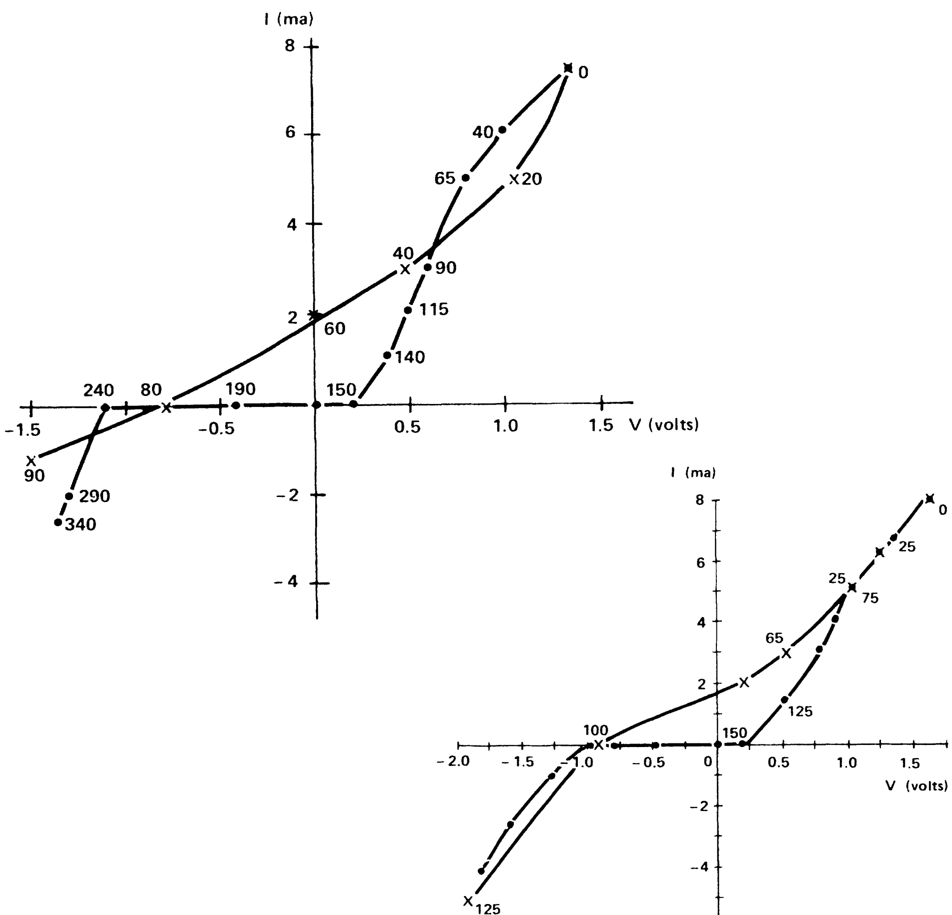

FIG. 4. The I-V curves developed from ramp interruptions, showing asymmetric TONC behavior for the slow ramp interruption (●) and almost straight-line behavior for fast ramp interruptions (× data points). Voltage measurements are more precise than in Refs. 1—5 because the voltage drop across the low-resistance current-measuring resistor is automatically subtracted from the voltage measurement, and because the current-measuring resistance is approximately equal to the average on-state resistance at the operating point (for circuit balance during dianostic probing).

high-conductance portion of a normal TONC.

It is evident that the on state of an OTS is maintained by some electronic process that is different from that which creates it. It is also known that the potential drop must be either near the contacts or in a narrow recombination front at or near the middle. This is clear from the observations that the on-state properties are virtually *independent* of thickness of the film. Whereas the off state is strongly temperature dependent, the on state is almost independent of ambient temperature.

There is, at this stage, no universally accepted interpretation of the on state as such. In the past, TONCS have always been recorded as symmetrical. However, if the on state were controlled essentially by two back-to-back barriers in series with bulk material of negligible resistance (because it is in gross electronic disequilibrium), then such asymmetry would by puzzling, if only because *identical* barriers are rare in real life. That particular difficulty has now been removed, but the observed asymmetries are found to be linked to time-dependent factors, and that link involves problems of its own. It is tempting (though at this stage admittedly speculative) to invoke trapping and de-trapping processes. Whatever contact barriers may be at work cannot be conventional Schottky barriers, partly because (in view of the insensitivity to temperature change) the barrier height would have to be quite low. The fast responses of an on state to temporary deformation (as reflected by the TONC) rules out any role for *deep* traps; indeed, it has been suggested (Adler, Mott, and Henisch[6]) that the two space-charge regions might arise entirely from an unbalanced free-carrier plasma. However, a role for shallow traps could still be envisaged, and in general terms one could argue along those lines that the classic TONC arises only when trapped charges are promptly liberated in response to the applied signal. However, when the ramp slope exceeds a certain critical value, insufficient time is available for this to happen, and the blocked on state then remains undeveloped. The asymmetry as such is undoubtedly of structural origin; it reverses when the specimen is reversed.

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