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Single fast-pulsed interruption of on state of amorphous threshold switch: I-V decay curve and trapped-carrier lifetime

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The on state of an amorphous threshold switching device has been analyzed during fast voltage descent from the on voltage through the holding voltage to zero. The resulting I-V characteristics show an initial region of Ohmic behavior, a subsequent region of transitional properties, and ultimately a region of residual voltage ascribed to space-charge asymmetry. These data indicate 10 nsec as the time for formation of the blocked on state through redistribution of the mostly trapped space charge at the blocked on threshold. The subsequent decay of the blocked on state in about 100 nsec takes place as the electrons recombine at the edges of their distribution with holes that flow in through the contacts. The observed positive residual bias implies an initial influx of Coulomb-attracted holes which is the greater through the anode contact, and this is consistent with the reported narrowing of the formed region of the diode near this contact. These results support the model of the space-charge on state due to electrons.

In previous cw studies[1,2] of the post-switching on state of amorphous threshold Ovonic switching devices, we have reported that the blocked on state—the high-impedance subregime of the transient on characteristics (TONC) (Refs. 3–5)—develops when the device voltage is beneath the holding level[6] for an excess of 10–20 nsec. These studies indicated that this subholding voltage time could be readily interpreted in terms of a lifetime of trapped or localized carriers. They indicated also that if the voltage is between the holding voltage and 0 for no longer than about 10–12 nsec, then the resulting I-V characteristics are essentially metal-like and approximately linear through the origin. The purpose of the present paper is to compare pulse data with the cw data, with particular reference to physical mechanisms involved in the development and decay of the blocked on state. The pulse data on this decay show a residual bias voltage whose interpretation may afford new insights in support of the physical model.

The present study investigated the same Ovonic threshold switching devices that were addressed before[1,2] but utilized the more revealing technique of a single diagnostic pulse, rather than a cw, to establish the I-V characteristics during fast voltage descent in the on state to zero field. The diagnostic probing pulse was applied to the device on state through the circuit given in Fig. 1. A clean noiseless probing pulse was obtained through the use of matching resistors in the pulser output circuits and through careful grounding and isolation. All data were plotted in a point-by-point fashion as a function of time into the interruption.

Typical I-V data taken as a function of time into the diagnostic probing pulse are given in Fig. 2. The probing pulse itself was a negative square pulse of 55-nsec rise time, 150 to 300 nsec in width, and 3.1 V in magnitude (exactly equal and opposite to the on voltage). The insets to the figure show (a) typical switching and diagnostic pulse in terms of voltage and current versus time, (b) an expanded scale of the device voltage and current during the interruption from the on voltage to zero, (c) the voltage and current during a diagnostic pulse using a 100-Ω dummy resistor rather than the amorphous switching device, (d) the switching I-V (from curve tracer) to show the holding voltage of 1.65 V, and (e) the on state I-V at 500 kHz to show the offset or barrier voltage of 1.2 V.

The I-V curve itself taken during the interruption displays linear behavior capable of extrapolation through the origin, until after about 8–13 nsec of subholding voltage. The departure from Ohmic behavior shown in Fig. 2 from $t = 48$ to

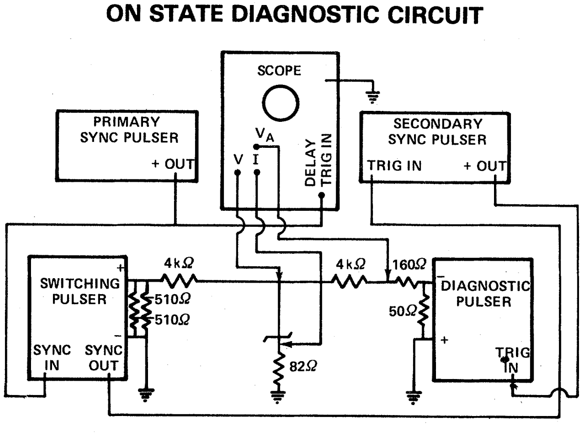

FIG. 1. Circuit schematic for diagnostic probing pulse study of the on state I-V-t characteristics of an Ovonic threshold switching device.

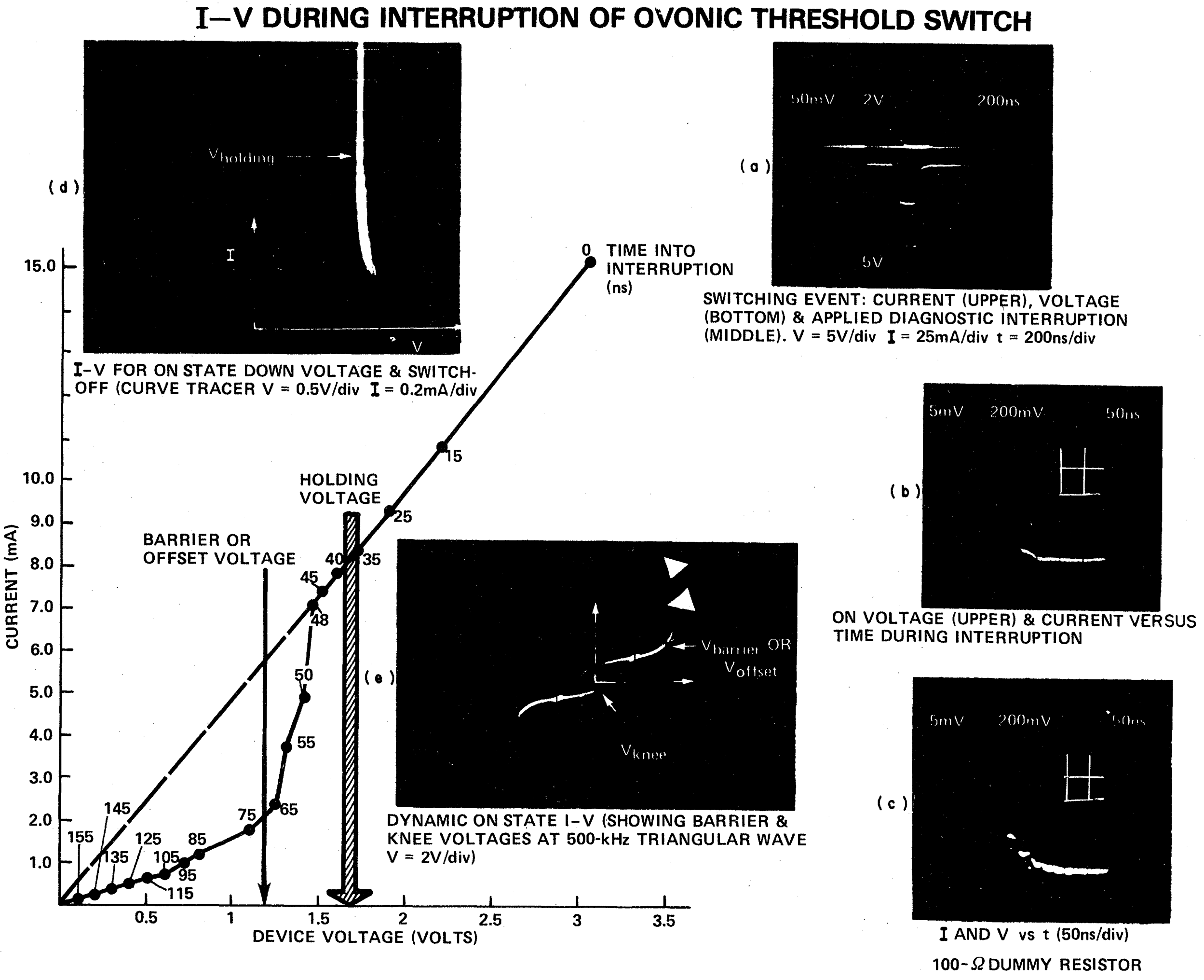

FIG. 2. Current in mA versus device voltage in volts as a function of time into the interruption (from zero to about 155 nsec). Note transitional region from 48 to about 70 nsec linking higher-voltage Ohmic regime with lower-voltage blocked on state. The sharp decrease in current corresponding to the transitional regime occurs after voltage is beneath holding level for an excess of about 10 nsec. Insets show (a) interruption voltage and current versus time, (b) sharp slope change in current at knee condition accompanying monotonic voltage, (c) the exact following of current on voltage for a dummy resistor (100 ohms) substituted for device, (d) decreasing voltage and current for on state at 120 Hz giving holding voltage, and (e) dynamic on state giving current versus voltage and showing barrier and knee voltages at 500 kHz.

75 nsec is a regime of sharply decreasing current accompanied by a slightly decreasing voltage. At $t = 75$ nsec (about 30 nsec below the holding voltage) the blocked on state is established at the TONC barrier or offset voltage and shows a superlinear behavior until $t = 100$ nsec, and thereafter essentially linear behavior to the origin. The blocked on state point-by-point region in Fig. 2 has an appearance similar to that of the dynamic blocked on state (sometimes called the transient off state) shown in inset (e).

It should be noted that although the rise time of the probing pulse (from $V = 0$ to -3.1 V) is about 55 nsec as measured across the right-hand resistor (4 kΩ) as shown in Fig. 1, the device voltage does not fall to zero until about 150 nsec into the interruption. The additional 100 nsec correspond to the decay of the blocked on state, during which a simultaneously decaying residual forward bias remains as a result of mechanisms which will presently be described. While the dielectric relaxation time of the device in its full on state has been calculated and measured to be much shorter (about 10^{-11} sec),[1,2] this same time-constant parameter at the blocked on-state threshold is the observed 8–13 nsec, and essentially the emission time τ_1, which apparently controls the redistribution of space charge at the threshold. τ_1 is then believed to be approximately the emission time of electrons in shallow traps. The redistribution occurs over the entire bulk. It was previously suggested[4] that this redistribution results in high-resistance regions at the contacts.

What is new and interesting from the pulse measurements in Fig. 2 relates to the nature of the slower τ_2 decay lasting about 100 nsec following the sharp τ_1 decay. This slower decay shown by the data points in Fig. 2 between $t = 70$ and 155 nsec can be interpreted as a residual bias. These data lie on a reasonably smooth curve, without scatter, hence a positive residual voltage is clearly obtained. It can be argued that no voltage should exist across the device during the decay of this charge, provided the diode were a uniform filament and the charge in it symmetrically distributed in the blocked on state. Thus the observed residual, ultimately "Ohmic," voltage decay should be associated with asymmetry of the device. This is in accord with our earlier reported observation of asymmetric electroluminescence.[5] The structural asymmetry of the filament has been previously described as approximately that of a truncated cone with the larger diameter at the cathode. The interpretation also reinforces the contention that the on state is *maintained* by a single-carrier distribution—electrons.

It should also be noted that in the context of the coupled carrier equations[7] for the approximation of uniform concentrations, at the threshold of the blocked on state or beginning of the τ_2 decay, a critical trapped-electron concentration is obtained. This concentration may correspond to what is reported by others[4] as the formation of the high-resistance regions at the contacts. The same description could hold whether single injection or Mott screening be the exact cause of the switching transition. The actual trapping probably occurs at nonuniformities such as valence-alternation pairs or impurities.[8]

It should not be surprising that the point-by-point data in Fig. 2 do not show any anomalous behavior at the true holding voltage (1.65 V) because the device does not "know" that the voltage has fallen beneath the holding level until the emission time or trapped-carrier lifetime τ_1 is exceeded. The present study gives this time as 8–13 nsec, in agreement with the earlier cw studies.

This work suggests that the region in Fig. 2 from 0 to 35 nsec into the interruption corresponds to the I-V characteristics of the true on state, and that the region from the holding voltage to about 48 nsec approximates the trapped-carrier emission time. The ensuing transitional range from about 48 to 60 nsec appears to correspond to the decay of trapped electrons back to valence-band sites. The essentially linear I-V range below the barrier voltage to zero seems to be related to residual charge from a critical trapped-electron concentration which requires the time interval τ_2 to undergo recombination to the valence band.

These decays in both the transitional and linear ranges are due to recombination of electrons in regions near the contacts with holes that flow in from the contacts. The decays must be transport dependent because hole concentration in the on region is quite small, being suppressed by quasi-steady-state recombination in near balance with the thermal generation. In the transitional range the positive or forward residual bias is established and reaches a maximum, and this positive bias implies an initial influx of holes which is the greater through the anode contact. In the final linear range, the residual bias and the blocked on-state electron distribution decay together as electrons recombine with holes near the contacts or at the edges of the on-state distribution. Because of the residual bias most of the recombination takes place near the anode contact. This asymmetry is what one would expect from the reported asymmetry of the formed region of the diode, namely, the narrowing of this region toward the anode contact. Thus, holes are more strongly Coulomb-attracted by electrons near this contact since electron concentration is greater there than near the cathode. The present results and their interpretation are in cogent support of the space-charge model of the on state due to electrons.

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[6] The true holding voltage was taken as the minimum voltage in 120-Hz full-wave operation in the threshold

on-state down-voltage direction prior to the inception of the current-controlled negative region just before the switch-off transition. The significance and magnitude of this voltage (V_h) should not be confused with the lower magnitude barrier or offset voltage which occurs at the knee of the characteristics between the high-conductance on state and the lower-conductance blocked on state.

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[8] G. C. Vezzoli, Phys. Rev. B 22, 2025 (1980).