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Direct Infrared Measurements of Filament Transient Temperature during Switching in Vanadium Oxide Film Devices

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Static and dynamic filament temperature profiles are shown in VO_2 film devices. The thermal switching is the consequence of the semiconductor to metal transition at 68°C arising from the fact that a conductive filament develops across the VO_2 device after switching. By use of an ir microscope, we have experimentally demonstrated large temperature spikes (some hundred degrees C) at the onset of switching in the growing filament. This maximum transient temperature (which may be destructive) is reached a few tens of microseconds after the generation of the filament. The external circuit parameters have a strong influence on this behavior. We have related this maximum filament temperature to the magnitude of the voltage drop during breakdown.

Introduction

Thermal switching (*1*) devices have been widely investigated in the past, particularly for VO_2 thin film devices because of a semiconductor to metal transition occurring at about 68°C. Experiments have confirmed that a conducting high temperature filament develops after breakdown (*2*). The width of this filament, at equilibrium, is a linear function of the total current flowing through the device. The characteristics of a static filament are elucidated at this time, but little is known about the transient behavior of a growing filament. Our purpose is to describe the different steps of this growth during the drop from high to low resistance in the specimens.

Measurements

An ir radiometric microscope with a 20 μm spatial resolution is used to measure the target radiance. The total emitted radiance is a function of the temperature as well as of the target emissivity. The VO_2 semiconductor-to-metal transition at 68°C causes the emissivity to be discontinuous, as shown in Fig. 1. Temperature calibrations below 68°C are not meaningful because VO_2 films in the semiconducting phase are transparent to the ir radiation, so that the emission of the substrate reaches the detector.

The VO_2 films are RF sputtered onto silica substrates, and aluminum film electrodes delineate a "gap." The interelectrode spacing is 100 μm and the electrode length is approximately 2.5 mm. Film thicknesses are in the neighborhood of 1500 Å.

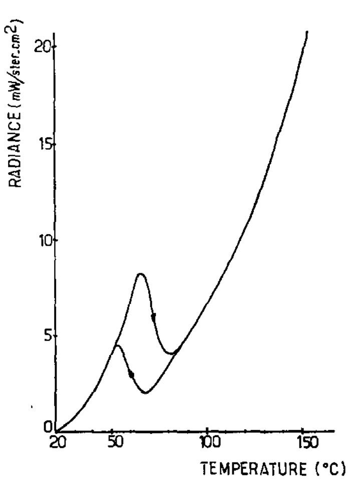

FIG. 1. Emitted radiance vs temperature for a typical 1500 Å VO_2 film deposited onto a silica substrate.

Static Behavior of the Filament

The static current–voltage curve of such a device is shown in Fig. 2. A stable filament appears after the threshold at a point of the conducting branch imposed by the external load.

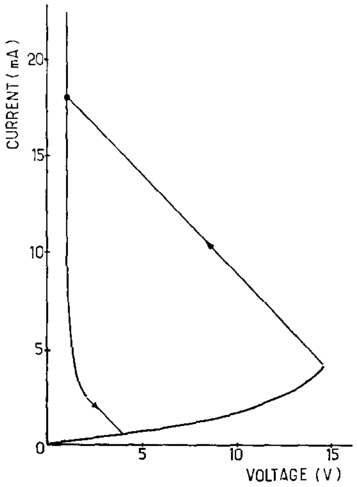

FIG. 2. Static I–V curve of a VO_2 device. Device length is 2.6 mm and interelectrode spacing is 100 μm. (Load lines are shown as straight lines both for off–on and on–off switchings.) $R_{load} = 1\ k\Omega$.

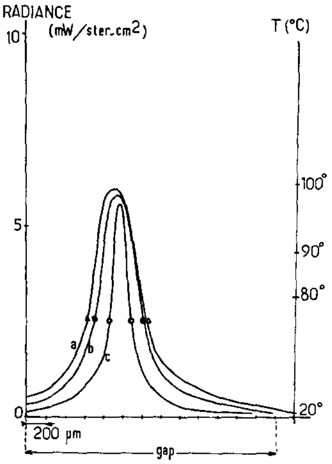

FIG. 3. Measured static radiance (and temperature) profiles at the center of the interelectrode spacing at three different operating points in the on state. The dots on the three profiles show the high temperature phase boundaries as determined by direct visible observation. (a) 60 mA 0.8 V; (b) 50 mA 0.8 V; (c) 30 mA 0.9 V.

The temperature profiles in the filament are shown in Fig. 3 at different operating points after breakdown. Again, the values below the transition temperature are not well determined. The maximum temperature remains nearly at 100°C when the current is increased. Dots on the profiles indicate the filamentary boundaries of the metallic phase. The development of such narrow filaments is a consequence of the large conductivity discontinuity between the inner and the outer portion of the filaments.

Transient Temperature Profiles

Our analysis was based upon the use of two different types of measurement: the electrical behavior of the device during switching, and the simultaneous recording of the temperature at any point in the growing filament.

The device as operated with square voltage pulses is analyzed below.

The pulse repetition rate is constant at 10 Hz and the pulse duration is 5 ms. After application of a pulse, a delay occurs in reaching the critical temperature of 68°C at some point in the film, generally a defect. This delay, in our case, was about 1 ms. Subsequently, a filament with a high current density begins to develop; the voltage drops and the current increases, along a load line determined by the external resistance.

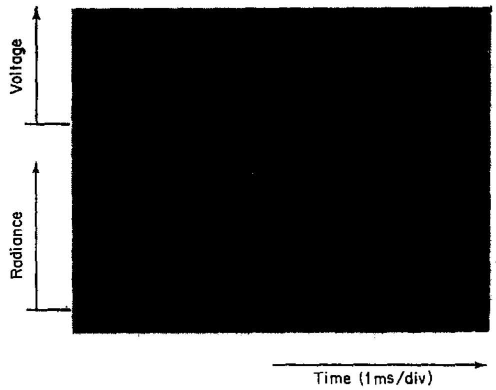

FIG. 4. Oscillogram showing simultaneously the VO_2 device voltage (20 V/div) (upper trace) and the radiance signal (200 mV/div) at the ir detector (lower trace) during the pulsed operation.

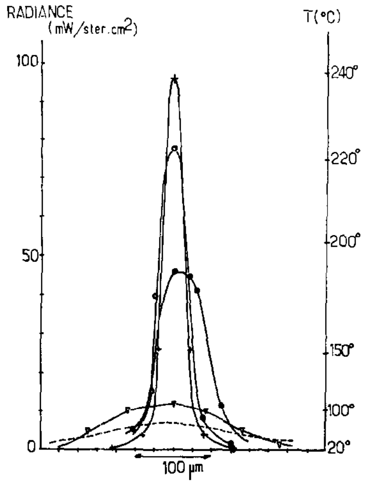

FIG. 5. Transient radiance (or temperature) profiles along the VO_2 device. The time parameter is counted from the onset of switching when voltage begins to drop. The dotted profile is the equilibrium one, with a filament width about 300 µm. + 20 µs; ○ 100 µs; ● 500 µs; ▽ 5 mS.

The oscillogram of Fig. 4 shows simultaneously the device voltage on the upper trace and the ir detector signal on the lower trace. During the time delay before switching, the device temperature is everywhere too low to produce any observable signal, but when the voltage drops, a large temperature signal appears and then decreases to the steady-state value around 100°C.

We repeated the measurements at different points across the filament. Figure 5 shows the evolution with time of the temperature profile across the interelectrode spacing. Time is again counted from the threshold. One should note the evolution from a narrow high temperature filament to a broader one at lower temperature. The maximum temperature reached after 20 µs is around 240°C for this specimen but values as high as 550°C have been measured just before destruction of the film along the filament. We have observed a strong dependence of the maximum transient temperature on the external parameters such as load and driving voltage.

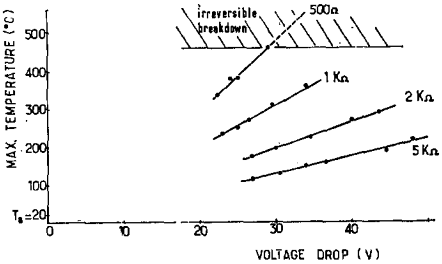

FIG. 6. Maximum transient temperature in the growing filament versus the voltage drop at switching on the same device.

A correlation between the maximum temperature in the filament and the voltage drop after switching has been obtained as shown in Fig. 6. The results are given for the same device with different pulse voltage and load resistors. The maximum temperature increases quasilinearly with the voltage drop at a given load. For a given voltage drop this temperature varies as the reciprocal of the load resistance. Near 500°C, the film melts at the center of the filament.

Discussion

Several authors (*3*, *4*) have predicted temperature spikes in the growing filament at switching. Our experimental data verify the occurrence of such an overheating effect in VO_2 filamentary devices. The lack of detailed calculations at this time is due to the difficulty of solving the transient thermal equation. We shall therefore only try to provide some qualitative explanations of the observed phenomena. The occurrence of such a temperature spike has been predicted to occur as a consequence of capacitive energy released into the active zone at switching. This theoretical approach consists in adding an electrostatic energy term to the thermal equation.

However, we believe that such a heating effect could only be significant during the first nanoseconds, and that simple Joule heating in the conductive filament is probably sufficient to explain most of the experimental features. Some tens of milliwatts are sufficient to heat the filament above 300°C in a few microseconds, provided that the Joule heating rate is greater than the thermal diffusion rate during the earlier steps of the filament growth. The current density increases in the conductive path at a rate determined by the actual resistance of the path and by the limiting action of the load circuit (that is to say the filament resistance to the load resistance ratio). This dependence of the filament transient temperature on the rate of increase of current density explains the effects of both the voltage drop and load resistor. Therefore, thermal diffusion becomes significant, and this leads to the spreading of the temperature distribution.

Conclusion

The key parameter of the filament formation in VO_2 devices is the existence of an electrical discontinuity with temperature. The steepness of this discontinuity gives rise to significant overheating of the filament before any appreciable thermal diffusion has occurred. In practical applications, one must counteract this overheating effect in thermal switching devices. Indeed, we have often observed destruction of samples in VO_2 devices, even when the final steady-state filamentary temperature was as low as 100°C.

References

1. Published literature is so abundant on this subject that we cannot provide all of the references. See, for instance, the special issue on amorphous semiconductor devices which appeared in *IEEE Trans. Electron. Dev.* **ED-20**, No. 2 (1973).
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