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Electron emission and memory effects in M-SiO/SnO_2-M devices

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Abstract : Thin film sandwich structures of M-SiO/SnO_2-M were studied with Cu and Al as metal electrodes. The complex dielectric materials SiO/SnO_2 were prepared by co-evaporation technique. The sandwich were electroformed at between 1.5 and 5 V irrespective of the composition of SiO/SnO_2 films. Electroformed M-SiO/SnO_2-M devices show a differential negative resistance, electron emission in a vacuum, voltage memory and pressure memory effects. The results are interpreted using a filamentary model. The effect of composition and thickness of SiO/SnO_2 films on the maximum current (I_{max}) and maximum power dissipation (P_{max}) were also investigated.

Keywords : Voltage memory, pressure voltage memory, electron emission

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Recently, considerable attention has been drawn to Metal-Insulator-Metal (MIM) devices which show a number of interesting properties such as differential negative resistance, electron emission in a vacuum, memory and switching effects. Much early work was carried out using Al_2O_3 [1] and SiO [2], where electroforming and Voltage Controlled Negative Resistance (VCNR) were observed. Voltage-memory effect on a formed Al-SiO-Al devices has been observed by Simmons and Verderber [2]. Such effect has also been observed by Hogarth and Ilyas [3] in Cu-SiO/TiO-Cu devices. The pressure-voltage memory effect has been observed by Emmer [4] on Al_2O_3. Abidi and Hogarth [5] and Hogarth and Ilyas [3] have observed the switching from a low resistance state to a high resistance state when the pressure was increased to 760 torr from 10^{-5} torr in BaO-SiO and SiO-TiO systems. The M-SiO/SnO_2-M devices had not been previously studied after electroforming the device. In this paper, we report the characteristics of M-SiO/SnO_2-M devices after electroforming.

The complex dielectric oxide films SiO/SnO_2 were prepared on Corning glass by using co-evaporation technique developed by Hogarth and Wright [6]. The active area of each device was 0.08 cm^2. Tantalum and Tungsten boats were used for the evaporation of SiO and SnO_2 respectively. The evaporation rates were monitored using quartz crystal monitor. Cu and Al electrodes were evaporated from molybdenum boat and tungsten spiral respectively. The forming experiments were performed in a vacuum of about 10^{-5} torr. A copper plate placed vertically at 1.5 cm above the substrate and biased at +100 V with respect to base electrode was used to measure the emission current using a Keithley electrometer (model 610C). The circulating current was measured by an Avometer type EA 133 and the potential difference across the sample was monitored by a Farnell digital multimeter (model DMM3). The thickness of the films were measured using multiple beam interferometry method.

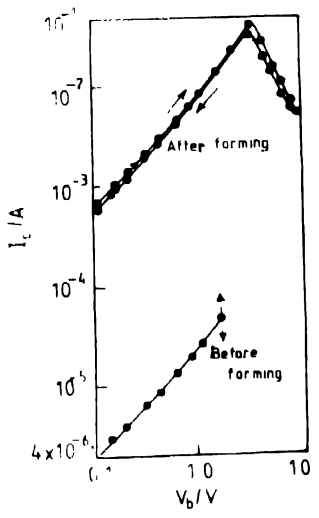

Figure 1. Current-voltage characteristics of a Cu-90 mol%SiO / 10mol%SnO_2-Cu device (insulator thickness 250 nm), before and after electroforming.

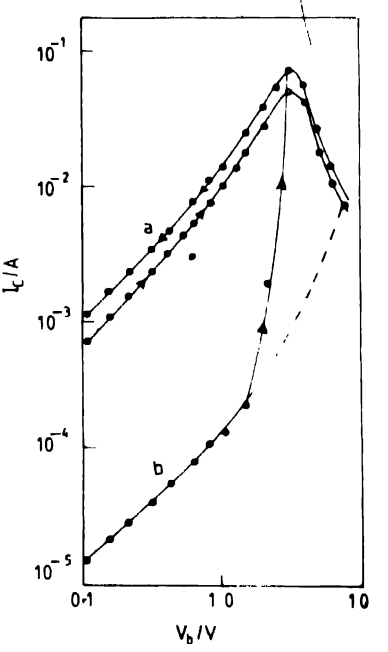

Figure 2. Current-voltage characteristics of an electroformed Cu-95mol%SiO / 5mol%SnO_2-Cu (insulator thickness 250 nm) sample showing voltage-memory effect, (a) initial formed characteristics, (b) memory state induced at 7V.

A typical current-voltage (I_c–V_b) characteristics of a Cu-90mol% SiO / 10mol% SnO_2-Cu (insulator thickness 250 nm) device before and after forming is shown in Figure 1. The (I_c- V_b) characteristics initially show ohmic character below 0.6 V and non-ohmic character above 0.6V but at an applied voltage of 1.5 V the current starts to fluctuate and increases rapidly which indicates that electroforming has started. A very stable and reproducible (I_c- V_b) characteristics with differential negative resistance in the (I_c–V_b) curve is obtained as shown in 'formed' part of Figure 1. It is evident from this figure that the current

increases by more than two orders of magnitude after electroforming of the device. The effect of composition and thickness of SiO/SnO_2 film on the maximum current (I_{max}) and maximum power dissipation (P_{max}) are given in Table 1. No systematic change of I_{max} with composition was found, but it may be observed that, in general, thicker films displayed low power dissipation at I_{max} and the results were consistent with the result reported earlier by Hogarth and Taheri [7].

Table 1. Some parameters of SiO/SnO_2 thin films after electroforming of the device with Cu electrode

Composition (mol%)		Film thickness nm	Forming voltage V	Voltage for maximum current	Maximum current A	Maximum power diss mW
SiO	SnO_2					
95	5	480	3	5	1.1×10^{-3}	5.5
95	5	380	2	4	4.6×10^{-2}	184
95	5	250	2	3	8.0×10^{-2}	240
90	10	250	1.5	3	9.0×10^{-2}	270
85	15	250	1.5	3	6.8×10^{-2}	204
70	30	500	2	6	3.8×10^{-2}	228

Figure 2 shows a voltage memory effect of a Cu-95mol% SiO / 5mol% SnO_2-Cu device. Curve b in Figure 2 shows the high resistance state ('OFF' state). This state is stable and reproducible provided that the threshold voltage (V_{th} ~ 1.5 V) is not exceeded.

The system may be transformed from the high resistance 'off' state into the original low resistance 'on' state using a voltage supply $V_b > V_{th}$. The ratio of resistance of these states is estimated as 1.5×10^2 (from Figure 2).

Figure 3 shows a I_c–V_b characteristic after forming of an Al-90 mol% SiO/10 mol% SnO_2-Al (insulator thickness ~ 250 nm) device at different pressures (from 10^{-5} torr to 760 torr). It may be seen that at atmospheric pressure the current follows the same path as recorded at 10^{-2} torr upto a certain critical voltage (V_T). Increasing the voltage above V_T the current decreases and the development of a high resistance state occurs. During the reverse run (reducing voltage form 8 V to 0 V) the system conductivity is significantly reduced and the I_c–V_b characteristic become monotonic (curve C in Figure 3). The high resistance memory state remains unchanged during further voltage cycles, as long as the sample is kept at high pressure (760 torr). When the chamber is evacuated again to 10^{-5} torr and I_c–V_b characteristics recorded from 0 V, the current shows the same value as recorded at 760 torr but only upto the threshold voltage (V_{th} ~4 V). Beyond V_{th} (~4 V) the I_c–V_b characteristics again sharply returns to 'form' values of the I_c–V_b curves for the vacuum regime of 10^{-5} torr.

The variation of emission current I_e and circulating current I_c with applied voltage is shown in Figure 4 for Cu-90 mol% SiO/10 mol% SnO_2-Cu device. The emission current is increased 3 orders of magnitude (from 10^{-9} to 10^{-6} A) when the applied voltage is increased

from 7 V to 13 V (Figure 4). The emission current density at room temperature is found to be approximately 50 A cm $^{-2}$ for a Cu-95 mol% SiO/5 mol% SnO_2-Cu device (insulator thickness 380 nm) with a maximum bias voltage of 13 V.

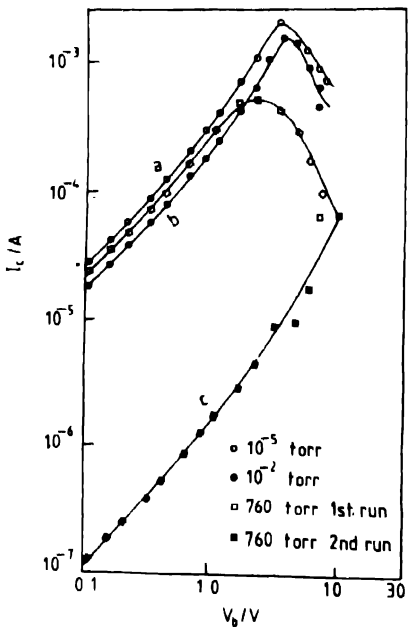

Figure 3. Effects of varying ambient air pressure on the I_c–V_b characteristics of a formed Al-90 mol%-SiO / 10 mol%SnO_2-Al (insulator thickness 250 nm)

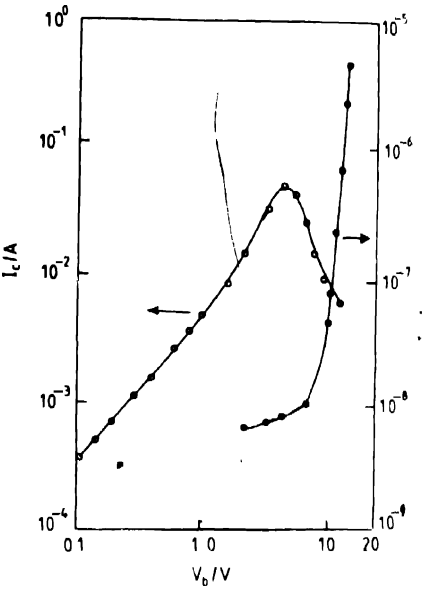

Figure 4. Variation of circulating current (I_c) and emission current (I_e) as a function of applied bias for a Cu-95 mol%SiO / 5mol%SnO_2-Cu (insulator thickness ~ 380 nm) device.

The observation of electroforming, voltage-controlled negative resistance and electron emission can all be interpreted on the basis of filamentary conduction model as originally suggested by Dearnaley *et al* [8]. During the forming process, a large number of metallic filaments develop from the anode through the insulator to the cathode and bridge the interelectrode space. The filaments created are not perfectly uniform but contain weak points and they become heated due to the flow of electrons. At higher voltages significant power will be dissipated resulting in an easy rupture of filaments at their weak points due to Joule heating. As a result the conductivity is reduced and a differential negative registance region developed in the I_c–V_b curve. During reverse voltage cycle (maximum to minimum) the current increases again due to re-growth of filaments by some kind of ionic migration. Therefore reproducible I_c–V_b characteristics were obtained with increasing and decreasing voltages.

Dearnaley *et al* [8] suggested that electron emission may be due to the generation of hot electrons at the weak points of the filaments near the anode by the application of high electric field. These hot electrons then emerge from the top electrode (anode) into a vacuum.

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