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Effects of insulating layer on the performance of thin film electroluminescent devices

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Abstract. Thin film electroluminescent devices were fabricated with active layer of ZnS:Mn and different insulators viz Sm_2O_3, Eu_2O_3, Na_3AlF_6, MgF_2, CeO_2 and SiO in MIS and MISIM structure. The threshold voltage for light emission in AC thin film electroluminescent devices of MIS and MISIM structures is found to depend on the dielectric properties of insulating materials. The observed threshold voltage for these devices and its variations for devices with different insulators are explained using the equivalent circuit for the device and the dielectric properties of the insulting material used for the preparation of device. Variation of threshold voltage with operating time is also studied for some of the devices.

Keywords. Electroluminescent devices; threshold voltage; insulating layer.

1. Introduction

AC thin film electroluminescent (ACTFEL) devices have been actively investigated in recent years (Inoguchi and Mito 1977; Lehmann 1980; Kutty 1985) since they exhibit a number of attractive properties such as low power dissipation and fast response along with the possibility of providing large area, completely solid-state multicolour flat panel displays. The most popular double insulating devices have high brightness ($> 1000\ cd/m^2$) and long life (~ 2000 h) but require operating voltages of about 150 volts (Inoguchi and Mito 1977).

Devices based on metal-insulator-semiconductor structure (MIS) have been suggested as one way of reducing the driving voltage of the TFEL devices (Kozawaguchi *et al* 1982). According to Howard (1977), to obtain high brightness and better efficiency for these devices, the insulator film must satisfy the condition that the product of its dielectric constant (ε) and breakdown voltage must at least be three times higher than that of the active layer. This implies that low voltage operation can be obtained without sacrificing the brightness or efficiency by using insulators of high dielectric constant and preferably with high breakdown strength. The performance of ACTFEL devices depends on the thickness of ZnS:Mn layer (Tornqvist *et al* 1983). The threshold voltage can be reduced either by reducing the thickness of insulating layer or active layer or both. In order to fabricate legible low voltage and high brightness TFEL devices in MIS structure with ZnS:Mn, insulating layers of different figure of merit (Sm_2O_3, Eu_2O_3, Na_3AlF_6, MgF_2, CeO_2, and SiO) have been investigated here. For low voltage and high brightness the optimal thickness of ZnS layer and insulator (in the case of Eu_2O_3 and Sm_2O_3

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films) is found to be for a thickness ratio lying between 1 and 2 (Jayaraj and Vallabhan 1990a). This suggests the possibility of lowering the voltage using insulators of high figure of merit in MIS-structured devices.

2. Experimental

The schematic structure of the TFEL device is shown in figure 1. A ZnS:Mn phosphor layer is evaporated on to a SnO_2-coated glass substrate by electron beam evaporation. The ZnS:Mn phosphors were prepared in the laboratory by a slurrying technique (Jayaraj and Vallabhan 1989a). The transparent electrodes were prepared by spray pyrolysis. Any one of the insulating layers of Sm_2O_3, Eu_2O_3, MgF_2, Na_3AlF_6, SiO, and CeO_2 was deposited by electron beam evaporation. During deposition the substrate temperature was kept at 423 K. The experimental investigations were carried out using a TFEL cells of emitting area $0{\cdot}5 \times 1\ cm^2$. A variable frequency sine/square wave generator was used to excite the cell along with a series resistor 100 K ohm which limits the current through the device. The EL emission spectra were recorded with the help of a 0·5 m Jarrel-Ash scanning spectrometer coupled with an EMI9683 KQB photomultiplier tube (PMT) having S-20 cathode. The PMT current was amplified with low noise high gain PMT preamplifier (Pillai and Vallabhan 1982) and recorded by a strip chart recorder. The EL emission intensity was measured using a PMT with S-1 cathode. For capacitance and loss factor measurements, thin films of about 2000 Å were made in sandwich structure between two aluminum electrodes having an area $1\ cm^2$. The capacitance and loss factors were measured using a LCZ meter (Hewlett-Packard 4277A) under a vacuum of 10^{-2} torr.

3. Results and discussion

The EL spectra of all the devices are the same as those of conventional ITO-Y_2O_3-ZnS:Mn-Y_2O_3-Al device (Inoguchi and Mito 1977). The brightness voltage (BV) characteristics of the device with MgF_2 and Eu_2O_3 insulating layers shows that the threshold voltage for the onset of emission increases with increase of excitation frequency (in the present experiments frequency was varied from 50 Hz to 5 kHz). This anomalous behaviour is explained elsewhere (Pillai and Vallabhan 1986; Jayaraj and Vallabhan 1990a). Figure 2 shows the B/V characteristics of the MIS devices with an active layer thickness 0·3 μm and insulator thickness 0·2 μm fabricated under similar conditions. It is observed that the threshold voltage for the onset of emission decreased with decrease of ZnS:Mn active layer thickness. This

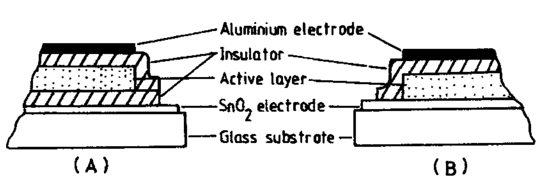

Figure 1. Structure of a typical TFEL (A) MISIM, (B) MIS device.

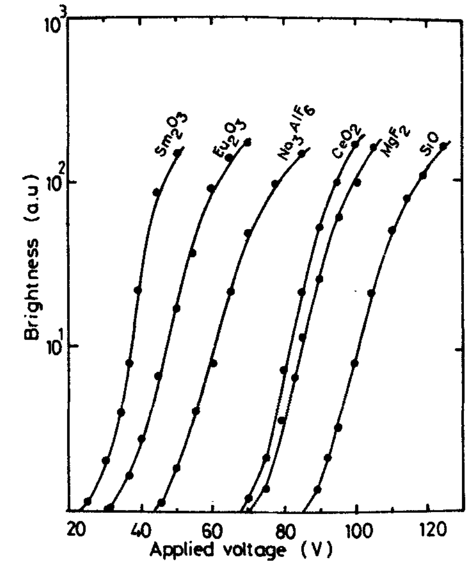

Figure 2. BV characteristics of MIS TFEL devices with different insulating layers under 1 kHz sine wave excitation.

was again reduced with the reduction of insulator thickness (whereas the brightness is found to increase with increase of ZnS:Mn layer thickness). Thus the driving voltage of TFEL devices can be reduced either by reducing the thickness of active layer or insulator or both. But when the insulator layer is too thin there is a possibility of breakdown while thick layers of insulator requires higher operating voltage. The optimal condition for MIS structure devices for low voltage operation is when the thickness ratio between active layer and insulator layer lies between 1 and 2. A detailed discussion on this aspect is given elsewhere (Jayaraj and Vallabhan 1990a). The brightness of a typical EL cell is estimated in absolute units using a PMT having a spectral response closely matching the sensitivity of human eye and it is found to be 1450 ft-lamberts.

The BV characteristics of metal-insulator-semiconductor-insulator-metal (MISIM) devices with ZnS:Mn 0·6 μm and insulator layer of 0·3 μm is shown in figure 3. From the slope of BV characteristics (figures 2 and 3) it can be seen that the doubly insulated TFEL devices show a steep increase in brightness when the applied voltage exceeds a certain threshold; whereas in MIS TFEL devices the brightness increases steeply. In both types of devices the brightness level saturates at high applied voltages. The MIS TFEL device has no insulator between one of the electrodes and the ZnS layer. Hence carriers could readily be injected from the electrode or released from the layer with the result that no carriers will accumulate near ZnS electrode interface, whereas in MISIM devices the charge will be stored at ZnS-insulator interface. As a consequence electric field induced by space charge at the ZnS-insulator layer add to the electric field produced by the applied voltage (Ogawa *et al* 1984). The trapped holes inside the ZnS layer can generate an internal field which increases the probability of electrons tunnelling through the ZnS-insulator barrier. Moreover, TFEL device being a capacitive load, conduction current which contributes to luminescence is different at high voltages due to

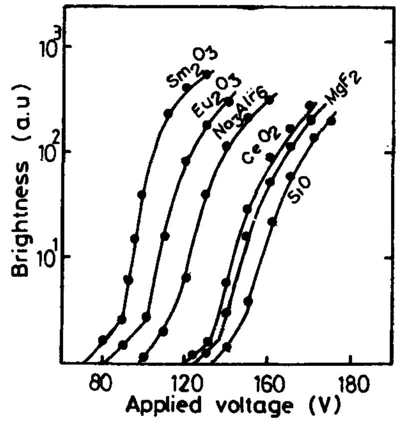

Figure 3. BV characteristics of MISIM TFEL devices with different insulating layers under 1 kHz sine wave excitation.

Table 1. Threshold voltage V_{th} for MISIM and MIS TFEL devices and dielectric constants and breakdown strength of insulator used for device fabrication.

Material	Thickness (μm)	ε	Breakdown strength V/cm ($\times 10^6$)	V_{th} for MISIM TFEL device (volts)	V_{th} MIS TFEL device
Sm_2O_3	0·2	43	2	80	25
Eu_2O_3	0·2	15–21	2	90	30
Na_3AlF_6	0·2	6·6	2·6	100	45
CeO_2	0·2	4·8	3	120	65
MgF_2	0·2	4·9	2	125	70
SiO	0·2	3·2–5·2	2	130	80

nonlinear effects. These factors may account for the sudden increase in slope of the BV curves observed for MISIM structures.

From the BV curves it is also clear that the threshold voltage for the onset of emission is different for devices with different insulators. The threshold voltage (V_{th}) for the onset of emission depends on the dielectric properties of the materials used and is minimum for devices with Sm_2O_3 and Eu_2O_3 as insulators while it is high for devices with SiO as insulator. Table 1 gives the materials used here as insulating layer in TFEL devices, their dielectric constants and the respective threshold voltage for MISIM and MIS structured devices. This variation of threshold voltage for different insulating layers, can be explained by making use of the equivalent circuit of the device as shown in figure 4. The TFEL can be considered as two series capacitance C_i and C_s due to insulator and the active layer respectively. Here R_i is an additional resistance included to account for the leakage currents. It can be visualized that if V is the applied voltage and U the voltage appearing across the active layer, then

$$U = Z_s/(Z_s + Z_i)\,V \tag{1}$$

where Z_i and Z_s are the impedance of the insulating and active layers. At a

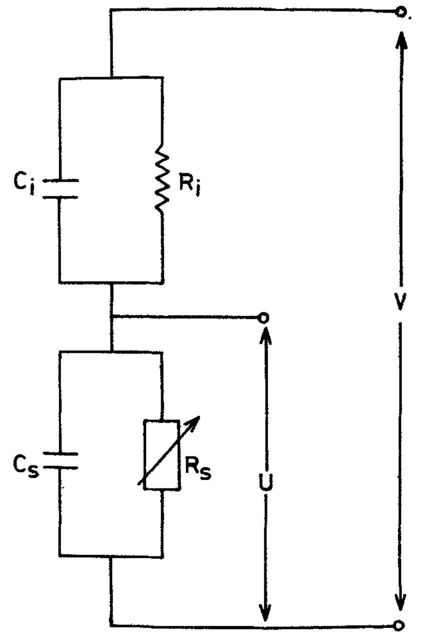

Figure 4. Equivalent circuit.

particular frequency ω

$$U_{\mathrm{th}}=\frac{Z_s(\omega)}{Z_i(\omega)+Z_s(\omega)}\,V_{\mathrm{th}}, \tag{2}$$

$$U_{\mathrm{th}}=\frac{R_s(1+C_i\omega R_i)}{R_s+R_i+\omega R_iR_s(C_i+C_s)}\,V_{\mathrm{th}}. \tag{3}$$

Assuming the leakage resistance to be very high

$$U_{\mathrm{th}}=C_i/(C_i+C_s)\,V_{\mathrm{th}}.$$

Here C_s is constant since the active layer (in the present case ZnS:Mn films having dielectric constant ε about 7) of same thickness is used in all the devices while C_i is different because the insulator layers used are materials with different dielectric constant even though the thickness is the same in all the cases. However U_{th} i.e. the threshold voltage for the onset of emission (or voltage across the active layer) is a constant. Devices with insulators of high dielectric constant will have high C_i value which in turn increases the applied voltage for the onset of emission (V_{th}) as determined by (4) since U_{th} has to remain constant. This evidently explains the low threshold voltage for the onset of emission for devices with Sm_2O_3 insulating film which has a higher value of ε ($\approx$42).

3.1 *Ageing effects*

It is a well known fact that threshold voltage for TFEL devices increases with operating time and then gradually becomes constant (Inoguchi *et al* 1977). Ageing of more than 100 h has been required to stabilize the device characteristics. In the present case, devices with Sm_2O_3 and Eu_2O_3 as insulating layers were subjected to ageing studies. It is observed that, in the case of devices fabricated with insulators (Sm_2O_3 and Eu_2O_3) and active layer (ZnS) deposited at higher substrate temperature ($T_s = 423$ K) do not show any appreciable variation in threshold voltage with ageing or operating time (figures 5 and 6). But devices prepared with same insulators deposited at a lower substrate temperature ($T_s = 300$ K) and active layer at 423 K show marked variation in the threshold voltage. This phenomenon can also be accounted for in terms of the dielectric properties of the insulating materials. The dielectric constant of Eu_2O_3 and Sm_2O_3 prepared at $T_s = 300$ K decrease with ageing time. The rare earth oxide films require prolonged annealing of about 200 h to have a stable dielectric constant (Nakane *et al* 1979). It is found that Eu_2O_3 and Sm_2O_3 prepared at substrate temperature 423 K will have a dielectric constant and loss factor which are independent of ageing time. These films deposited at higher substrate temperature exhibit better dielectric properties owing to improved stoichiometry of the films (Jayaraj and Vallabhan 1989b, 1990b). The variation of ε with time for Sm_2O_3 and Eu_2O_3 films prepared at 423 K and 300 K are shown in figures 5 and 6. The threshold voltage varies with operating time for devices prepared with insulators at $T_s = 300$ K because ε decreases with ageing time which in turn changes C_i and hence V_{th}, while device prepared at $T_s = 423$ K do not

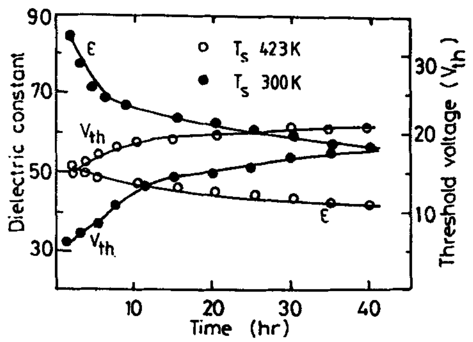

Figure 5. Variation of V_{th} and ε (at 1 kHz) with ageing time for Sm_2O_3-based MIS TFEL device.

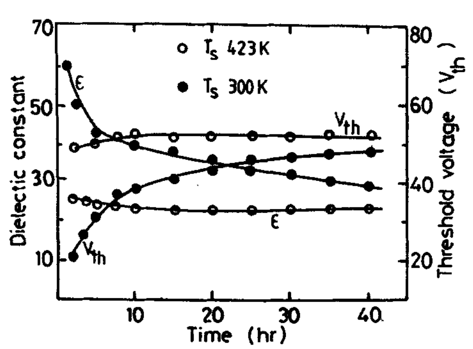

Figure 6. Variation of V_{th} and ε (at 1 kHz) with ageing time for Eu_2O_3-based MIS TFEL devices.

show any variation in threshold voltage. C_s, the capacitance due to ZnS layer, is almost a constant and hence it does not affect the operating characteristics of the device. Hence the variation of V_{th} is due to variation in insulating film properties.

4. Conclusions

TFEL devices with MIS structure as well as double insulating MIS structure have been fabricated using ZnS:Mn as an active layer and different insulators. Sm_2O_3 is a better insulator for low voltage operation without loss in brightness and EL emission characteristics. The threshold voltage for the onset of emission is low for Sm_2O_3-based devices, while it is high for SiO-based devices. This behaviour is attributed to the high dielectric constant of the insulating material used in the fabrication of devices. Devices in which Sm_2O_3 or Eu_2O_3 deposited at higher (423 K) substrate temperature do not show significant variation in threshold voltage with ageing time.

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