Relaxation charge anomalies in the charge–voltage characteristics of alternating-current thin-film electroluminescent devices

P. D. Keir, H. Le, R. L. Thuemler, J. Hitt, and J. F. Wager[a]
Department of Electrical and Computer Engineering, Center for Advanced Materials Research, Oregon State University, Corvallis, Oregon 97331-3211

(Received 21 May 1996; accepted for publication 7 August 1996)

Anomalous charge–voltage $(Q-V)$ characteristics are observed for several types of alternating-current thin-film electroluminescent (ACTFEL) devices. These $Q-V$ curves are anomalous because conduction charge flows in these devices exclusively during the portion of the wave form in which the applied voltage is constant, at its maximum value; this kind of conduction charge is denoted relaxation charge. In a normal ACTFEL device, most of the conduction charge flows during the portion of the wave form in which the applied voltage increases with time. The anomalous $Q-V$ characteristics are attributed to insulator leakage for the devices tested. Simulation shows that such anomalous behavior may arise from either insulator or phosphor leakage. © *1996 American Institute of Physics.* [S0003-6951(96)04842-5]

The charge–voltage $(Q-V)$ technique is the most commonly used method for accomplishing electrical characterization of alternating-current-thin-film electroluminescent (ACTFEL) devices.[1] Recently, we have measured the $Q-V$ curves of several different types of ACTFEL devices which exhibit unusual $Q-V$ characteristics. The purpose of this letter is to describe the nature of these anomalous $Q-V$ curves and to offer an explanation for their origin.

A set of three anomalous $Q-V$ curves is shown in Fig. 1 for an ACTFEL device in which the phosphor layer is SrS grown by metal-organic chemical-vapor deposition (MOCVD). The ACTFEL device is grown on a glass substrate with an indium–tin–oxide bottom electrode, an aluminum–titanium–oxide (ATO) bottom insulator, an electron-beam-evaporated Y_2O_3 top insulator, and an aluminum top electrode. The primary anomalous attributes of these curves are the absence of turn-on, the absence of an above-turn-on regime in which the slope of the $Q-V$ curve is equal (or at least approximately equal) to the insulator capacitance, and that conduction charge flows in this device (as evidenced by hysteresis in the $Q-V$ curve) but that all of this conduction charge is due to relaxation charge (see the following for a discussion of relaxation charge).

In contrast to the anomalous curves shown in Fig. 1, a more typical $Q-V$ curve is shown in Fig. 2 for a ZnS:Mn ACTFEL device grown by atomic layer epitaxy with ATO insulators. An alphabetical labeling scheme is employed in Fig. 2 in order to identify important points in the $Q-V$ loop.[2] A comparison of Figs. 1 and 2 provides a detailed picture of how the Fig. 1 curves are anomalous. In Fig. 2, note that points B and G, which are distinguished as the intercepts of the slopes of straight line sections of the $Q-V$ curve and which define the turn-on voltages, are absent in the $Q-V$ curves shown in Fig. 1. Next, observe that the BC and GH portions of the $Q-V$ curve shown in Fig. 2 are not seen in the $Q-V$ curves of Fig. 1. In a typical ACTFEL device, BC and GH are the portions of the wave form during which the majority of the conduction charge flows across the phosphor. Also, the slope of the $Q-V$ curve in the BC or GH regime is approximately equal to the insulator capacitance since the capacitance of the phosphor is shunted by the flow of current across the phosphor. At first glance, the lack of turn-on voltages and BC and GH regimes in Fig. 1 seems to imply an absence of conduction charge flow in these devices; however, hysteresis is clearly present in Fig. 1, so this cannot be the case. In fact, all of the charge transported in the $Q-V$ curves shown in Fig. 1 is relaxation charge, corresponding to the CD and HI portions of the $Q-V$ curve shown in Fig. 2. The relaxation charge is conduction charge which flows across the phosphor during the portion of the wave form in which the applied voltage is constant and at its maximum value. This fraction of the conduction charge is termed relaxation charge since the phosphor field relaxes during this portion of the wave form.[3,4] This is in contrast to conduction charge which flows during the BC and GH portions of the wave form, which occurs during the rising edge portion of the wave form. Relaxation charge is usually considered to be a nonoptimal form of conduction charge since this portion of the charge is transported at a lower average phosphor-field than the conduction charge which flows during the BC or GH portions of the $Q-V$ curve.

After observing this kind of anomalous behavior for several types of ACTFEL devices with differing phosphors, we

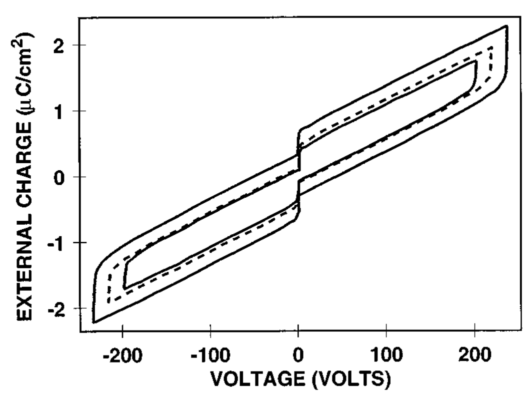

FIG. 1. An anomalous set of $Q-V$ curves for a SrS ACTFEL device.

[a]Electronic mail: jfw@ece.orst.edu

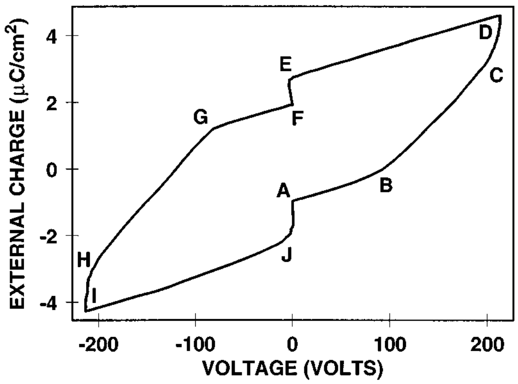

FIG. 2. A normal $Q-V$ curve for an ALE ZnS:Mn ACTFEL device. The alphabetical labeling scheme is used to identify certain important points in the $Q-V$ curve.

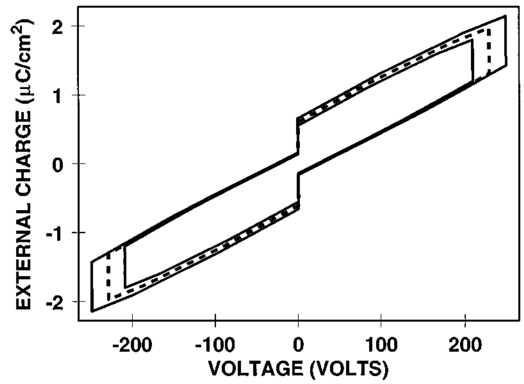

FIG. 3. A simulated $Q-V$ curve for an ACTFEL device in which the top insulator capacitance is shunted by a 100 kΩ resistor.

suspected that the poor quality of the Y_2O_3 was responsible for the anomalous behavior, since all of the devices tested which exhibited these kinds of $Q-V$ curves had Y_2O_3 upper dielectrics. Indeed, substitution of the Y_2O_3 dielectric with a high-quality silicon oxynitride dielectric grown by plasma-enhanced CVD yielded ACTFEL devices with normal looking $Q-V$ characteristics. However, in the process of trying to determine the source of these $Q-V$ anomalies, SPICE simulation[5] was performed which yielded further insight into the nature of these anomalies.

The SPICE simulations are performed assuming a very simple model for the ACTFEL device consisting of three capacitors in series, representing the bottom and top insulators and the phosphor; additionally, one of these layers is shunted by a resistor to account for leakage. In the SPICE simulations, the bottom and top insulator capacitances are 4.74 and 8.69 nF, respectively, and the phosphor capacitance is 0.616 nF. The SPICE simulations are accomplished using a sense capacitance of 110.8 nF (a sense capacitor is placed in the measurement circuit to monitor the transferred charge[1]) and a series resistance of 500 Ω (a series resistance is often placed in the measurement circuit to minimize the probability of catastrophic breakdown of the ACTFEL device). Note that these SPICE simulations are performed without the inclusion of back-to-back Zener diodes, or alternative circuit elements which model the flow of conduction charge across the phosphor, since it is assumed that the anomalous behavior is not associated with normal charge injection.

A simulated $Q-V$ curve in which a 100 kΩ resistor shunts the upper insulator capacitor is indicated in Fig. 3. Note that this simulated $Q-V$ curve is anomalous and exhibits most of the peculiar attributes evident in the anomalous $Q-V$ curves shown in Fig. 1 (i.e., conduction charge which is exclusively relaxation charge, no turn-on, and no insulator capacitance regime). Thus, it is evident from a comparison of Figs. 1 and 3 that the anomalous $Q-V$ behavior shown in Fig. 1 arises from leakage across the upper Y_2O_3 insulator. Note that the 100 kΩ resistor used to model leakage in the upper insulator corresponds to a resistivity of $\sim 10^8\ \Omega$ cm. Thus, the quality of the insulator must be very poor before effects such as shown in Fig. 1 are observable. Finally, note that the same type of $Q-V$ curves as shown in Fig. 3 may be simulated by assuming that the lower insulator or the phosphor are leaky. This underscores the importance of having phosphor and insulator layers with high resistivities for ACTFEL applications.

In summary, abnormal $Q-V$ curves are reported in which conduction charge flows but all of the conduction charge is relaxation charge; additionally, no turn-on voltage or above-turn-on insulator capacitance regime is observed. These anomalous $Q-V$ curves are attributed to leakage of the upper insulator for the ACTFEL devices investigated. Anomalous $Q-V$ behavior is expected for ACTFEL devices in which the phosphor or either of the insulators are leaky.

This work was supported by the U.S. Army Research Office under Contract No. DAAH04-94-G-0324 and by the Defense Advanced Research Projects Agency under the Phosphor Technology Center of Excellence, Grant No. MDA 972-93-1-0030.

[1] Y. A. Ono, *Electroluminescent Displays* (World Scientific, Singapore, 1995).
[2] J. F. Wager, A. A. Douglas, and D. C. Morton, in *Electroluminescence*, edited by V. P. Singh and J. C. McClure (Cinco Puntos, El Paso, TX, 1992), p. 92.
[3] A. A. Douglas and J. F. Wager, in SID 92 Digest 1992, p. 365.
[4] A. A. Douglas and J. F. Wager, *Electroluminescence*, edited by V. P. Singh and J. C. McClure (Cinco Puntos, El Paso, TX, 1992), p. 387.
[5] SPICE (simulation program with integrated circuit emphasis) is a computer-aided design circuit simulator.