Offset of the electrical characteristics of alternating-current thin-film electroluminescent devices

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Offset is observed in the charge–voltage ($Q-V$) or internal charge–phosphor field ($Q-F_p$) characteristics of certain alternating-current thin-film electroluminescent (ACTFEL) devices. This offset arises from a displacement along the voltage axis of a transient curve measured across a sense capacitor in the electrical characterization setup. A procedure for adjusting this offset is proposed that allows ACTFEL devices manifesting offset to be meaningfully analyzed. Two possible sources of offset are deduced from simulation and are associated with an asymmetry in the interface state energy depths at the two phosphor–insulator interfaces or with an asymmetry in the location of space charge generation in the phosphor. *© 1996 American Institute of Physics.* [S0003-6951(96)03239-1]

Two techniques commonly used for the electrical characterization of alternating-current thin-film electroluminescent (ACTFEL) devices are charge–voltage ($Q-V$)[1] and internal charge-phosphor field ($Q-F_p$)[2] analysis. Recently, we have observed an unusual offset of both $Q-V$ and $Q-F_p$ curves when electrically characterizing certain types of ACTFEL devices. The purpose of this letter is to discuss the nature and possible physical origins of this offset and to present and an adjustment procedure that allows experimental data to be meaningfully analyzed when offset is present.

A set of $Q-F_p$ curves obtained at different temperatures for a ZnS:Mn ACTFEL device grown by atomic layer epitaxy (ALE) are shown in Fig. 1.[3] The originally measured $Q-F_p$ curves exhibit offset but the curves shown in Fig. 1 have been offset adjusted (as discussed in the following). Note that all of these offset-adjusted $Q-F_p$ curves are symmetrically centered about the origin. However, prior to performing this offset-adjustment procedure, the 100 K curve was displaced slightly downward and to the left of the origin (we denote this as a negative offset) whereas the 200, 300, and 400 K $Q-F_p$ curves are displaced upward and to the right of the origin (we denote this as a positive offset) by varying amounts.

The origin of $Q-V$ and $Q-F_p$ offset is indicated as Fig. 2. Offset is observed for devices in which the voltage transient measured across a sense capacitor (i.e., a sense capacitor is placed in series with the ACTFEL device and the voltage across the sense capacitor is monitored in order to evaluate the external charge transferred; this very common experimental arrangement is denoted as a Sawyer–Tower configuration[1]) is asymmetrical about the time axis. Such an asymmetrical voltage transient is labeled as the measured voltage in Fig. 2. [To obtain Fig. 2, a bipolar voltage pulse wave form is used; in Fig. 2 the onset of the positive and negative voltage pulses are denoted A and F, respectively, in accordance with conventional $Q-F_p$ labeling[2] (see Fig. 1 for a complete labeling of $Q-F_p$ curves). Note that there is a very long dead period between the positive and negative voltage pulses in which the voltage is zero; this portion of the wave form is omitted in Fig. 2 so that only the most relevant portions of the wave form are displayed.] If the sense capacitor voltage transient is displaced upwards along the voltage axis, as shown in Fig. 2, a positive $Q-V$ or $Q-F_p$ offset arises; for a downward voltage transient displacement, a negative $Q-V$ or $Q-F_p$ offset arises.

When interpreting $Q-V$ or $Q-F_p$ data for samples that exhibit offset, we have found it convenient to employ a procedure, which we denote an offset adjustment, which is accomplished by shifting the sense capacitor voltage transient curve until points A and F are equidistant about the time axis. Such an offset-adjusted sense capacitor voltage transient is indicated in Fig. 2. The advantage of such a procedure is that sets of $Q-V$ or $Q-F_p$ curves with differing amounts of offset can be meaningfully compared. Additionally, offsets can be compared by tabulating offset voltages.

An example of a situation in which this offset adjustment procedure is useful is shown in Fig. 1. After offset adjustment, it is clear from an analysis of Fig. 1 that the conduction charge, polarization charge, and peak phosphor electric fields all increase as a function of increasing temperature. However, it was impossible to establish these trends without first performing the offset correction. The offset voltage for the Q-F_p curves shown in Fig. 1 are -0.02 V

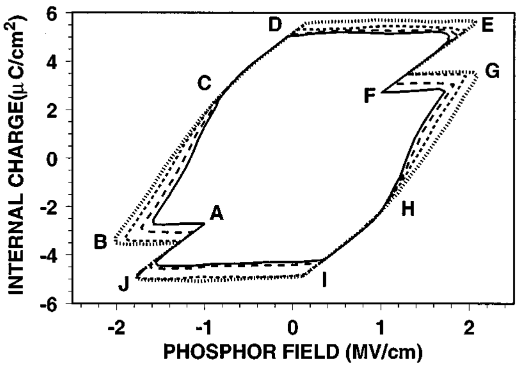

FIG. 1. Offset adjusted $Q-F_p$ curves for an ALE ZnS:Mn ACTFEL device at temperatures of 100, 200, 300, and 400 K. The inner $Q-F_p$ curve is for a temperature of 100 K and the outer $Q-F_p$ curve is for 400 K. The labels indicate critical points in the $Q-F_p$ curve.

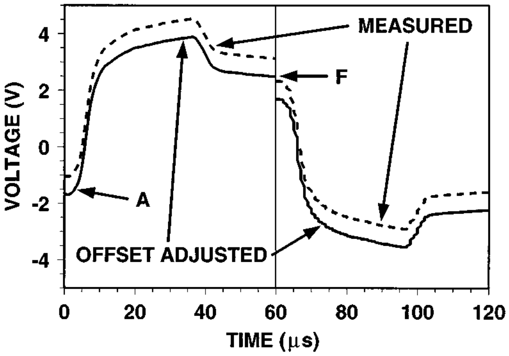

FIG. 2. Voltage transients measured across a sense capacitor for an ALE ZnS:Mn ACTFEL device that exhibits a positive offset and the same voltage transient after an offset adjustment. The *A* and *F* labels correspond to the onset of a positive and a negative applied voltage pulse, respectively, in accordance with conventional $Q-F_p$ labeling.

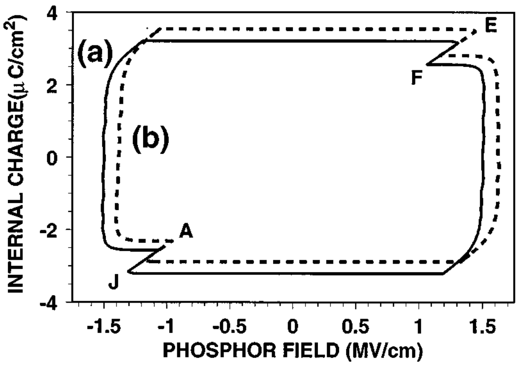

FIG. 4. Simulated $Q-F_p$ curves demonstrating that asymmetrical space charge generation can give rise to $Q-F$ offset. The sheet of space charge is located (a) 275 nm and (b) 50 nm from the lower interface. The total phosphor thickness is assumed to be 550 nm.

(100 K), +0.01 V (200 K), +0.20 V (300 K), and +0.65 V (400 K). Note that the offset increases with temperature in a nonlinear but monotonic fashion.

We have identified two physical sources that could be responsible for the presence of offset in measured $Q-V$ or $Q-F_p$ curves. The first source of offset is an asymmetrical interface state energy depth. Figure 3 shows a comparison of simulated $Q-F_p$ curves with discrete interface traps that have symmetrical or asymmetrical energy depths. The trap energy depths are 1.0 eV for the upper interface for both simulations whereas the energy depths of the lower interface are 1.0 and 0.9 eV for the symmetrical and asymmetrical interface state depths, respectively. The simulations are performed using the single-sheet charge model,[4] developed to model space charge generation in ACTFEL devices, except that no space charge generation is assumed in the present simulation. As seen in Fig. 3, a $Q-F_p$ curve is symmetrical about the origin if the interface state energy depths are equal but it exhibits offset if the interface state energy depths differ. Moreover, the magnitude of the voltage offset is a measure of the difference in the depths of the interface states and the polarity of the offset is an indicator of which set of interface states is deeper in energy. Simulation shows that a positive $Q-V$ or $Q-F_p$ offset is obtained if the interface states are deeper in energy at the upper interface; alternatively, a negative offset is found if the interface states are deeper in energy at the lower interface. (Note that we assume that the onset of a positive voltage pulse to the upper electrode occurs at point *A* in the $Q-F_p$ curves shown in Fig. 1.)

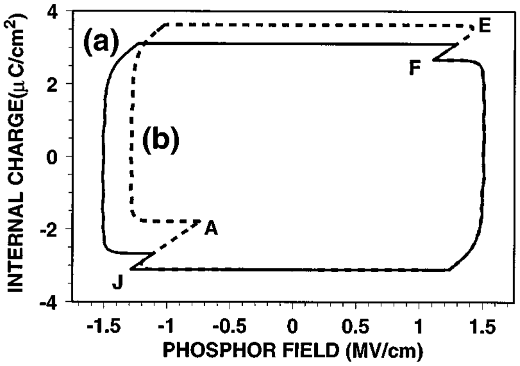

FIG. 3. Simulated $Q-F_P$ curves demonstrating that an asymmetrical interface state energy depth can give rise to $Q-F_p$ offset. A discrete interface state distribution is assumed. The energy depths are assumed to be 1.0 eV for the upper interface for both simulations whereas the energy depths of the lower interface are assumed to be (a) 1.0 eV and (b) 0.9 eV.

Alternatively, offset can arise in a device that exhibits space charge generation in the phosphor, if this space charge is created asymmetrically across the phosphor. Figure 4 shows two simulated $Q-F_p$ curves in which the space charge is generated symmetrically and asymmetrically across the phosphor. These simulations are also performed using the single-sheet charge model, assuming that space charge generation occurs via field emission from a bulk trap state.[4] The symmetrical $Q-F_p$ curve, Fig. 4(a), is simulated by assuming that the sheet of charge is located precisely at the center of the phosphor layer (275 nm from either interface). In contrast, the $Q-F_p$ curve shown in Fig. 4(b) with positive offset is generated assuming that the sheet of charge is 50 nm from the lower interface. Alternatively, a $Q-F_p$ curve with a negative offset may be simulated by assuming that the sheet of charge is displaced closer to the upper than the lower interface.

Two possible physical sources of $Q-V$ or $Q-F_p$ offset are identified and are associated with interface state energy depth asymmetry and space charge generation asymmetry. The nature of the symmetry or asymmetry of the leakage charge[2] (i.e., leakage charge is the difference in internal charge between points *EF* and *JA* in Figs. 3 and 4) provides a clue as to whether offset arises from interface state energy depth asymmetry or from space charge generation asymmetry. Note that when offset arises from interface state depth asymmetry, as shown in Fig. 3, that there is a noticeable asymmetry in the leakage charge [i.e., $Q_{\text{leak}}(JA) > Q_{\text{leak}}(EF)$], whereas the magnitude of the leakage charge is fairly symmetric when offset arises from space charge generation asymmetry [i.e., $Q_{\text{leak}}(JA) \sim Q_{\text{leak}}(EF)$]. With this observation in mind, it appears that at least some of the offset observed in the $Q-F_p$ curves shown in Fig. 1 is a consequence of an asymmetry in the interface state energy depth since $Q_{\text{leak}}(JA) > Q_{\text{leak}}(EF)$ for all of the curves shown in Fig. 1. However, some of the observed offset is undoubtedly due to space charge generation asymmetry also;

note that space charge generation is present in the $Q–F_p$ curves shown in Fig. 1, as evident from the noticeable amount of phosphor field overshoot at points B and G in the $Q–F_p$ curves.

When space charge generation is observed, it is not clear which of these two offset mechanisms dominates, since it is likely that they both contribute to the offset. Thus, it is usually difficult to determine how much of the offset is contributed by each mechanism. To date, we have observed only one situation in which offset appears to arise exclusively from interface state energy depth asymmetry; this was observed in a temperature-dependent study of a thiogallate: Ce ACTFEL device that exhibited a negative offset at temperatures in excess of ~400 K.[5] No evidence for space charge generation (i.e., no capacitance–voltage or $Q–F_p$ overshoot) was observed in the electrical characteristics of this device. Additionally, this thiogallate: Ce ACTFEL device is unusual since no leakage charge is present in this device; presumably, the lack of leakage charge is a consequence of having very deep interface states.[5,6]

In summary, offset in $Q–V$ or $Q–F_p$ characteristics is a consequence of a displacement about the time axis of the voltage transient measured across a sense capacitor. A simple offset adjustment procedure is proposed, which allows the electrical characteristics of ACTFEL devices that exhibit offset to be analyzed in a straightforward fashion. Simulation indicates that an asymmetry in the interface state energy depths and an asymmetry in the location of space charge generation are two possible physical sources that can lead to offset.

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