Abstract

Simulations of phosphor space charge in alternating-current thin-film electroluminescent (ACTFEL) devices are performed to determine the effect of space charge on electrical characteristics. The space charge distribution in the phosphor layer is modeled as a sheet of charge at an arbitrary location in the phosphor layer. Space charge creation is assumed to be caused by either field emission of electrons from bulk traps or impact ionization of deep-level traps in the phosphor layer. Simulation results show that phosphor space charge contributes to anomalous device characteristics such as overshoot in capacitance-voltage (C-V) and internal charge-phosphor field (Q-Fp) measurements.

Introduction

It has been speculated that space charge in the phosphor layer of alternating-current thin-film electroluminescent (ACTFEL) devices is the cause of certain anomalous behaviors exhibited by ACTFEL devices. Various researchers have conjectured that the hysteresis seen in brightness-voltage (B-V) curves and the overshoot seen in both capacitance-voltage (C-V) and internal charge-phosphor field (Q-Fp) measurements is caused by the creation of space charge in the phosphor layer. There are two major reasons why space charge is assumed to be present in ACTFEL phosphor materials. First, the high phosphor fields at which ACTFEL devices typically operate (~1.5-2.0 MV/cm) means that impact ionization of deep-level traps and field emission of electrons from bulk traps is likely. Also, the abundance of impurities and defects found in typical ACTFEL phosphor materials provides a large number of traps available for ionization, thereby setting up the possibility for creation of large amounts of space charge.

The purpose of the work reported herein is to determine the effects of space charge in the phosphor layer on certain electrical measurements. Prior researchers have shown through simulation that space charge creation in the phosphor layer is responsible for the negative resistance effect seen in ACTFEL devices. The specific goal of this work is to simulate the C-V and Q-Fp overshoot seen in the electrical characteristics of certain ACTFEL devices. This goal is accomplished using a single sheet of space charge to model the space charge distribution in the phosphor layer. The simulation results are consistent with measured trends in ZnS:Mn based ACTFEL devices grown by atomic-layer epitaxial (ALE) and elucidate the origin of C-V and Q-Fp overshoot. Moreover, the single sheet charge model presented herein may be extended to ACTFEL materials systems such as SrS:Ce and CaS:Eu in which space charge effects are much more dramatic than those exhibited in ZnS:Mn based ACTFEL devices.

The Single Sheet Charge Model

The simulations are performed assuming a one-dimensional device with the space charge in the phosphor layer lumped into a single sheet of charge at a specific location. This assumption is particularly well-suited to modeling devices in which the distribution of bulk traps and hence, space charge is skewed toward one side of the phosphor layer. A pictorial representation of a single sheet charge ACTFEL device model is shown in Fig. 1. In Fig. 1, the electric fields in each region are denoted by the subscripted “f” terms, whereas thicknesses and distances are denoted by the subscripted “d” terms. The subscripts used in Fig. 1, “i1”, “i2”, “p1”, and “p2” refer to insulator 1, insulator 2, phosphor layer 1, and phosphor layer 2, respectively. The model shown in Fig. 1 is then analyzed using Kirchhoff’s voltage law, Gauss’s law, and charge conservation to obtain the following set of six equations describing the electrostatics inside the ACTFEL device:

\[ d_{i1} f_{i1} + d_{p} f_{p1} + (d_{p} - d_{s}) f_{p2} + d_{i2} f_{i2} = -v_g \]  
(1)

\[ c_{i1} d_{i1} f_{i1} - c_{p} d_{p} f_{p1} = -q_1 \]  
(2)

\[ c_{p} d_{p} (f_{p1} - f_{p2}) = -q_{sc} \]  
(3)

\[ c_{p} d_{p} f_{p2} - c_{i2} d_{i2} f_{i2} = -q_2 \]  
(4)
The initial step in obtaining a dynamic model is the simultaneous solution of the six equations for the phosphor electric field components $f_{D1}$ and $f_{D2}$ (see Fig. 1). Then, the dynamic model is developed by differentiation of the electrostatic equations for $f_p$ and $f_g$ to produce a set of coupled first-order differential equations. This set of coupled differential equations describes the evolution of the phosphor field in both regions of the phosphor layer as a function of electron emission from each interface and the applied voltage waveform.

The emission of electrons from each interface is modeled assuming that both interfaces are discrete Coulombic wells. Electron emission rates from the insulator-phosphor interfaces are computed by taking the sum of the thermal emission rate and the emission rates due to phonon-assisted tunneling and pure tunneling. The emission rate of the space charge layer is modeled as either due to field emission or impact ionization of deep-level states. When field emission is the assumed method of space charge creation, the sheet of charge is treated as the product of the charge emitted from the emitting interface and a field-dependent multiplication factor. The distributed effect of impact ionization is translated to the single sheet charge model by using average fields for computation of the multiplication factor. In addition, the location of the sheet of charge is chosen as the centroid of the supposed charge distribution.

**Results**

The results of the simulation support the notion that C-V overshoot arises from the creation of space charge in the phosphor layer of an ACTFEL device. Figure 2 shows C-V plots from the results of two different simulations, one with space charge creation by impact ionization of deep-level traps, and the other without space charge creation. As seen in Fig. 2, a measurable capacitance overshoot occurs immediately following device turn-on when space charge is included in the simulation. The effect seen in Fig. 2 is similar to overshoot observed in ZnS:Mn devices grown by atomic layer epitaxy. The second C-V plot shown in Fig. 2 represents exactly the same simulation described above except that the number of bulk traps available in the phosphor layer is set to zero. The results shown in Fig. 2 indicate that no C-V overshoot is witnessed when space charge creation is not included.

The results of ACTFEL device simulations with space charge creation by field emission exhibit similar characteristics to those seen in Fig. 2. Figures 3 and 4 show two families of simulated C-V plots with a parametric variation of the location of the sheet of space charge within the phosphor layer. It should be noted that the C-V plots shown in Fig. 3 are performed with the Al electrode biased negatively. Alternatively, the C-V plots of Fig. 4 were created with the Al electrode biased positively. Figures 3 and 4 show that as the space charge layer becomes increasingly close to one of the insulator-phosphor interfaces, the Al+ and Al− C-V plots become increasingly asymmetrical. In fact, greater overshoot is witnessed when the space charge layer is located near the cathodic interface. This gives rise to devices whose electrical characteristics depend heavily on the polarity in which they are biased. Experimentally, polarity-dependent
characteristics are often seen in devices exhibiting space charge effects. Therefore, the skew of the space charge centroid towards one of the interfaces seems to be the cause of these asymmetrical device characteristics.

![Figure 3](image1.png)

**Figure 3.** Family of C-V curves for Al- (the arrow indicates increasing $d$: $d=50\text{nm}, 100\text{nm}, 150\text{nm}, 275\text{nm}, 400\text{nm}, 450\text{nm}, \text{and } 500\text{nm}$).

![Figure 4](image2.png)

**Figure 4.** Family of C-V curves for Al+ (the arrow indicates increasing $d$: $d=50\text{nm}, 100\text{nm}, 150\text{nm}, 275\text{nm}, 400\text{nm}, 450\text{nm}, \text{and } 500\text{nm}$).

The above results show that the creation of space charge in the phosphor layer of an ACTFEL device leads to overshoot in C-V measurements. Similar to the C-V measurement, the creation of space charge in the phosphor also leads to field overshoot in Q-F$_p$ measurements. Figure 5 shows two simulated Q-F$_p$ plots, one including space charge creation by impact ionization of deep-level traps, and the other not including space charge. The most noticeable effect seen in Fig.5 is the shift of the Q-F$_p$ plot to a position where it is no longer centered around the point where internal charge and phosphor field are zero. The other effect is the field overshoot witnessed for one polarity of the driving waveform. The overshoot in the Q-F$_p$ plot is much less pronounced than in the C-V measurement, so the location of the overshoot is pointed out by the label.

![Figure 5](image3.png)

**Figure 5.** Simulated Q-F$_p$ plots of an ACTFEL device with (a) space charge creation by impact ionization of deep-level traps and (b) no space charge creation included.

The issue of C-V and Q-F$_p$ overshoot can also be addressed quantitatively using Eqs.1 through 6. When Eqs.1 through 6 are solved self consistently for the time rate of change of $q_\phi$ and the resultant expression is divided by the time rate of change of the applied voltage, $v_p$, an expression for the measured capacitance of the ACTFEL device emerges. This expression is given by

$$C_m = \frac{c_i}{c_i + c_p} \left[ \frac{\partial q_\phi}{\partial v_g} + \left( 1 - \frac{d_s}{d_p} \right) \frac{\partial q_{\phi c}}{\partial v_g} \right] + c_i \tag{7}$$

where $q_\phi$ is the charge on the emitting interface, $d_s$ is the distance from the emitting interface, and $c_i$ is the total physical capacitance of the ACTFEL device. Equation 7 is important because it shows the relationships between the space charge related quantities and the measured capacitance. According to Eq.7, the nearer the space charge layer to the emitting interface, the greater the overshoot for the same amount of space charge creation. Also, Eq.7 shows that a static layer of space charge in the phosphor layer has no effect on the measured capacitance because the measured capacitance is only dependent on the change in space charge with respect to the change in the applied voltage.
Similarly, it is possible to use Eqs. 1 through 6 to solve for the phosphor field measured in a Q-Fp measurement. With this approach, the equation

\[ F_p = \frac{d}{d_r} F_{p1} + \left(1 - \frac{d}{d_p}\right) F_{p2} \quad (8) \]

is obtained. Equation 8 is fundamentally an equation for the average field inside of the phosphor layer, but when examined more closely shows that Q-Fp field overshoot is indeed related to C-V overshoot. Since the difference in the phosphor field is dependent on the amount of space charge contained in the phosphor, the magnitude of \( F_p \) is directly dependent on the amount of space charge. Then, as space charge is created during the rising edge of the driving waveform, the difference in fields will begin to increase, and the average field can be reduced after reaching an initial maximum.

Conclusion

The issue of space charge in ACTFEL devices is important from a device physics perspective because the magnitude and the location of the space charge determines the phosphor field distribution which, in turn, establishes the device brightness. While the existence of space charge in the phosphor layer has recently been a topic of considerable interest, very little work has focused on simulation of space charge effects or quantification of the amount and distribution of such space charge.

There are several implications of the simulation of phosphor space charge in the context of the above discussion. First, this simulation provides conclusive evidence that phosphor layer space charge generation causes C-V and Q-Fp overshoot. Second, information about the space charge distribution can be inferred from the shown parametric variations of space charge location. For example, experimental C-V plots can be compared with Figs. 3 and 4 to determine an approximate space charge location.

Acknowledgments

We wish to thank Shankar Pennathur for many useful discussions during the course of this work. This work was supported by the U.S. Army Research Office under Contract No. DAAH04-94-G-0324 and by the Advanced Research Projects Agency under the Phosphor Technology Center of Excellence, Grant No. MDA 972-93-1-0030.

References

P-26: Modeling Space Charge in ACTFEL Devices Using a Single-Sheet-Charge Model

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Abstract

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\[ d_{i1}f_{i1} + d_s f_{p1} + (d_p - d_s) f_{p2} + d_{i2} f_{i2} = -V_g \]  
\[ c_{i1} d_{i1} f_{i1} - c_p d_p f_{p1} = -q_1 \]  
\[ c_p d_p (f_{p1} - f_{p2}) = -q_{sc} \]  
\[ c_p d_p f_{p2} - c_{i2} d_{i2} f_{i2} = -q_2 \]
\[ c_1 d_1 f_{11} = -q_e \]  \hspace{1cm} (5) \\
\[ q_1 + q_2 + q_{\infty} = 0 \]  \hspace{1cm} (6)

The initial step in obtaining a dynamic model is the simultaneous solution of the six equations for the phosphor electric field components \( f_{p1} \) and \( f_{p2} \) (see Fig. 1). Then, the dynamic model is developed by differentiation of the electrostatic equations for \( f_{p1} \) and \( f_{p2} \) to produce a set of coupled first-order differential equations. This set of coupled differential equations describes the evolution of the phosphor field in both regions of the phosphor layer as a function of electron emission from each interface and the applied voltage waveform.

The emission of electrons from each interface is modeled assuming that both interfaces are discrete Coulombic wells.\(^\text{11}\) Electron emission rates from the insulator-phosphor interfaces are computed by taking the sum of the thermal emission rate and the emission rates due to phonon-assisted tunneling and pure tunneling.\(^\text{12}\) The emission rate of the space charge layer is modeled as either due to field emission or impact ionization of deep-level states. When field emission is the assumed method of space charge creation, the sheet of charge is treated as the product of the charge emitted from the emitting interface and a field-dependent multiplication factor. The distributed effect of impact ionization is translated to the single sheet charge model by using average fields for computation of the multiplication factor. In addition, the location of the sheet of charge is chosen as the centroid of the supposed charge distribution.

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![Figure 1](figure1.png)

**Figure 1.** Pictorial representation of an ACTFEL device containing a single sheet of space charge.

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\[
C_m = \frac{c_i}{c_i + c_p} \left[ \frac{\partial q_c}{\partial V_g} + \left( 1 - \frac{d_s}{d_p} \right) \frac{\partial q_w}{\partial V_g} \right] + c_i \tag{7}
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where \( q_0 \) is the charge on the emitting interface, \( d_s \) is the distance from the emitting interface, and \( c_i \) is the total physical capacitance of the ACTFEL device. Equation 7 is important because it shows the relationships between the space charge related quantities and the measured capacitance. According to Eq. 7, the nearer the space charge layer to the emitting interface, the greater the overshoot for the same amount of space charge creation. Also, Eq. 7 shows that a static layer of space charge in the phosphor layer has no effect on the measured capacitance because the measured capacitance is only dependent on the change in space charge with respect to the change in the applied voltage.
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References