Space charge generation in ZnS:Mn alternating-current thin-film electroluminescent devices

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The electrical characteristics of ZnS:Mn alternating-current thin-film electroluminescent (ACTFEL) devices grown by atomic layer epitaxy are assessed as a function of the thickness of the phosphor layer using capacitance-voltage (C-V) and internal charge-phosphor field (Q-Fp) analysis. Deviations from the ideal in the measured C-V and Q-Fp characteristics are ascribed to the generation of space charge in the phosphor layer during ACTFEL device operation. C-V overshoot deviations are correlated to space charge generation via a simulation employing a single sheet of charge model which assumes that the centroid of the generated space charge is located at a discrete sheet within the phosphor. Space charge generation in these atomic layer epitaxy (ALE) ZnS:Mn ACTFEL devices is ascribed to impact ionization of the zinc vacancy portion of chlorine-zinc vacancy self-activated defect complexes. A thermodynamic argument is provided which suggests that zinc vacancies are created via self-compensation of ZnS when the ZnS is unintentionally doped with chlorine. It is contended that space charge generation could even be desirable in ALE ZnS:Mn ACTFEL devices because it leads to better aging stability and improved performance. © 1995 American Institute of Physics.

I. INTRODUCTION

A constant electric field exists across the phosphor of an alternating-current thin-film electroluminescent (ACTFEL) device in the absence of space charge within the bulk portion of the phosphor. We have found that evaporated ZnS:Mn ACTFEL device performance can be explained adequately without invoking the existence of space charge, whereas the presently studied atomic layer epitaxy (ALE) ZnS:Mn ACTFEL device performance can only be understood if an asymmetrical amount of space charge creation is invoked (space charge creation is found to occur preferentially near the last grown interface).

The purpose of the work reported here is to present the results of a study of the electrical characteristics of ALE ZnS:Mn ACTFEL devices in which the phosphor layer thickness is varied. We find that the amount of space charge generation present in these devices under typical operating conditions increases with increasing thickness of the phosphor. Furthermore, it is our contention that an increased amount of space charge generation may be desirable in ALE grown ZnS:Mn ACTFEL devices because this leads to improved performance and better aging stability.

II. EXPERIMENTAL PROCEDURE

A. ACTFEL device structure

The three ACTFEL devices used for this study were fabricated at Planar International and were grown by ALE. Each ALE ACTFEL device consists of a phosphor layer sandwiched between two layers of aluminum-titanium oxide (ATO) and contacted by aluminum and indium-tin oxide (ITO) electrodes which are employed as top and bottom contacts, respectively. The ALE ACTFEL devices tested have phosphor thicknesses of approximately 230, 550, and 920 nm; these devices will be referred to as “thin,” “normal,” and “thick,” respectively, in the remainder of this article. The ATO thicknesses are approximately constant for all three devices tested and range from approximately 230 to 290 nm.

B. Electrical characterization

Electrical characterization of these ACTFEL devices is accomplished via capacitance-voltage (C-V) and internal charge-phosphor field (Q-Fp) analysis. Electrical characteristics are obtained using virgin dots and again after 24 hours of aging. C-V and Q-Fp curves are obtained for maximum applied voltages (Vmax's) of 60, 80, 100, and 120 V in excess of the threshold voltage, Vth. Vth is taken as the minimum applied voltage at which an appreciable amount of light is observed by the human eye. Al⁺ and Al⁻ denote the applied voltage polarity with respect to the aluminum electrode.

C. Capacitance semantics

In the subsequent analysis, it is important to carefully distinguish among three different kinds of capacitance: (i) the actual, physical capacitance, (ii) the effective capacitance associated with a C-V measurement, and (iii) the effective capacitance associated with Q-Fp measurements. This distinction among these different kinds of capacitance is necessary because in ACTFEL devices which exhibit effects related to space charge generation (as do all the ACTFEL devices tested in this study) the experimentally deduced capacitance is not identical to the actual, physical capacitance. Thus, we denote C1phys and C1pphys as the physical capacitances.
of the insulator layers and the phosphor layer, respectively; these capacitances are calculated from known values of the dielectric constant, $\varepsilon$, the cross-sectional area, $A$, and the layer thickness, $d$, via the parallel plate capacitor formula, $C = \varepsilon A/d$. From $C_i^{\text{phys}}$ and $C_p^{\text{phys}}$, the physical capacitance of the total phosphor stack, $C_i^{\text{phys}}$, is determined as

$$\frac{1}{C_i^{\text{phys}}} = \frac{1}{C_p^{\text{phys}}} + \frac{1}{C_i^{\text{phys}}}.$$  \hspace{1cm} (1)

In contrast to the physical capacitances defined above, we denote the insulator, phosphor, and total capacitances deduced via $C$-$V$ analysis as $C_i^{\text{c-v}}$, $C_p^{\text{c-v}}$, and $C_i^{\text{c-v}}$, respectively. As shown in Fig. 1, $C_i^{\text{c-v}}$ and $C_i^{\text{phys}}$ may be determined directly from a $C$-$V$ measurement whereas $C_p^{\text{c-v}}$ is calculated from an equation similar to Eq. (1). As is apparent from Fig. 1, $C_i^{\text{c-v}}$ is usually found to agree with $C_i^{\text{phys}}$ quite well, whereas $C_i^{\text{c-v}}$ and $C_p^{\text{phys}}$ are distinctly different.

Finally, $C_i^{\text{fp}}$ and $C_p^{\text{fp}}$ are effective capacitances deduced experimentally from a fit to the $Q$-$F_p$ curves as described in the following text. Figure 2 shows two $Q$-$F_p$ curves. Curve (a) is generated using $C_i^{\text{phys}}$ and $C_p^{\text{phys}}$ in the $Q$-$F_p$ equations; this leads to a $Q$-$F_p$ curve which is severely distorted from the expected, ideal case (we attribute this $Q$-$F_p$ distribution to space charge generation, as discussed later in the article). In contrast, curve (b) in Fig. 2 is a "normal-looking" $Q$-$F_p$ curve. Curve (b) is obtained by allowing the values of $C_i^{\text{phys}}$ and $C_p^{\text{phys}}$ to be freely adjusted so that the resulting $Q$-$F_p$ curve is as "normal-looking" as possible. Operationally, in order to obtain $C_i^{\text{fp}}$ and $C_p^{\text{fp}}$, a family of $Q$-$F_p$ curves is plotted first as a function of $C_i^{\text{fp}}$. $C_i^{\text{fp}}$ is chosen based on the value of $C_i^{\text{fp}}$ which yields the most horizontal AB/FG and DE/II sections of the $Q$-$F_p$ curves, where the labels A–J are indicated in Fig. 2. Curve (b). Next, a family of $Q$-$F_p$ curves are plotted as a function of $C_p^{\text{fp}}$. $C_p^{\text{fp}}$ is chosen based on the value of $C_p^{\text{fp}}$ which yields the most vertical BC/GH sections and the most horizontal AB/FG and DE/II sections of the $Q$-$F_p$ curves. Sometimes it is necessary to iterate several times in the fitting procedure to determine the optimal values of $C_i^{\text{fp}}$ and $C_p^{\text{fp}}$.

### III. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Result summary

The primary experimental results of this study are summarized in Table I in which the insulator and total capacitances, as estimated from the known physical thickness and dielectric constant, are compared to estimates which are deduced experimentally from the $C$-$V$ and $Q$-$F_p$ measurements.

<table>
<thead>
<tr>
<th>Physical capacitance</th>
<th>C-$V$</th>
<th>Q-$F_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al$^+$</td>
<td>Al$^-$</td>
</tr>
<tr>
<td>Insulator capacitance ($C_i$)</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>Total capacitance ($C_i$)</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Normal, $V_{bi}=123$ V</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>Thick, $V_{bi}=163$ V</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C-V</th>
<th>Q-$F_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$^+$</td>
<td>Al$^-$</td>
</tr>
<tr>
<td>Thin, $V_{bi}=100$ V</td>
<td>27</td>
</tr>
<tr>
<td>Normal, $V_{bi}=123$ V</td>
<td>38</td>
</tr>
<tr>
<td>Thick, $V_{bi}=163$ V</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
TABLE II. A comparison of the ratio of the effective insulator capacitance as deduced by C-V or Q-F_p measurements to the calculated physical insulator capacitance.

<table>
<thead>
<tr>
<th>Capacitance ratio</th>
<th>Applied voltage polarity</th>
<th>Thin</th>
<th>Normal</th>
<th>Thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{i eff}/C_{i phys}</td>
<td>Al⁺</td>
<td>1.2</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Al⁻</td>
<td>1.2</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>C_{i phys}/C_{i phys}</td>
<td>Al⁺</td>
<td>1.1</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Al⁻</td>
<td>1.2</td>
<td>1.7</td>
<td>2.2</td>
</tr>
</tbody>
</table>

ments. Note from Table I that there is fairly good agreement between the total capacitances C_{i phys}, C_{i cu}, and C_{ieff}. In contrast, there are significant differences between C_{i phys} and the insulator capacitances deduced from electrical measurements (i.e., C_{i cu}, and C_{i eff}) and these differences become more pronounced as the thickness of the phosphor increases. These differences between the physical insulator capacitance and that deduced from electrical measurements are more clearly indicated in Table II where the ratio of the insulator capacitance determined experimentally from C-V or Q-F_p measurements to the physical insulator capacitance is tabulated for the three ALE ZnS:Mn ACTFEL devices; these insulator capacitance ratios are also tabulated as a function of the applied voltage polarity. The clear message of Table II is that the capacitance ratio increases with increasing phosphor thickness; this trend is attributed to an increasing amount of space charge generation with increasing phosphor thickness, as discussed below. Finally, note from Tables I and II that there is only a moderate amount of asymmetry with respect to the applied voltage polarity in the experimentally assessed insulator and total capacitances. The lack of asymmetry evident in Tables I and II is misleading since the electrical characteristics typically are asymmetrical. Evidence for asymmetry is illustrated in Figs. 3 and 4 in which the C-V curves for both polarities are shown for the thin and thick ACTFEL devices, respectively. As shown in Figs. 3 and 4, a polarity-dependent asymmetry is observed for both samples.

As asserted in the previous paragraph from the data shown in Table II, the fact that the insulator capacitance ratio, as deduced from C-V and Q-F_p analysis, is greater than one implies that space charge creation occurs in the phosphor layer of these ACTFEL devices during device operation. Other evidence of space charge generation is witnessed in the raw experimental data as follows.

(i) Overshoot in the C-V characteristics, as shown in Figs. 1, 3, and 4. As shown in Figs. 1, 3, and 4, we observe two types of overshoot; in the first case (i.e., Figs. 1 and 3) the capacitance increases and saturates at a value greater than that of the physical insulator capacitance. In the second case (i.e., Fig. 4) the capacitance first increases to a value in excess of that of the physical insulator capacitance and subsequently decreases towards a value nearly equal to, or a bit larger than, that of the physical insulator capacitance.

(ii) Q-F_p distortion, as shown in Figs. 2 and 5. Figure 2 illustrates the dramatic nature of Q-F_p distortion if physical capacitances are employed in the Q-F_p equations. Figure 5 shows several Q-F_p curves obtained at various maximum applied voltages for the thin ACTFEL device. The Q-F_p curves shown in Fig. 5 are obtained by fitting the insulator and total capacitances but still exhibit a slight amount of overshoot and a lack of field clamping, both of which are further evidence of space charge generation during ACTFEL operation.
B. A simple analytical model for C-V overshoot due to space charge creation

Our evidence for the existence of space charge creation arises from deviations from the ideal in measured C-V and Q-F characteristics. The purpose of this section is to present a simple, single sheet charge model which illustrates how one of these deviations, namely C-V overshoot, arises when space charge generation occurs in the phosphor layer. Further details of the single sheet charge model are provided in Ref. 8.

The single sheet charge model is shown in Fig. 6. Space charge in the phosphor is represented as a single sheet of charge of magnitude \( q_{sc} \) located at a distance \( d_s \) from the cathode interface. \( q, f, \) and \( d \) denote charge density, electric field, and thickness, respectively. The subscripts \( i \) and \( p \) denote insulator and phosphor, respectively, and the interfaces are denoted \( c \) and \( a \) for cathode and anode, respectively.

The single sheet charge electrostatic problem amounts to solving the following set of equations simultaneously:

\[
\begin{align*}
\frac{\partial q_i}{\partial t} + J_{p1}(t) d_s + J_{p2}(t) (d_p - d_s) + J_{f2}(t) d_{f2} &= -q_x(t), \\
q_i d t f_i(t) - q_p d f_p(t) &= -q_e(t), \\
q_p d f_p(f_i(t) - f_{p2}(t)) &= -q_w(t).
\end{align*}
\]

Equations (2) is Kirchhoff's voltage law, Eqs. (3)-(6) are the electrostatic boundary conditions, and Eq. (7) is an expression which accounts for the charge balance. Solving this set of equations for the external charge, \( q_e(t) \) and then differentiating this expression with respect to time yields

\[
\frac{\partial q_e}{\partial t} = \frac{c_{i1} c_{i2} d_p \frac{\partial q_i}{\partial t} + (c_{i1} c_{i2})(d_p - d_s) \frac{\partial q_{sc}}{\partial t} + c_{i1} c_{i2} c_p d_p \frac{\partial v_x}{\partial t}}{(c_{i1} c_{i2} c_{i1} c_p + c_{i2} c_p) d_p}.
\]

Denoting the measured current density as \( J_m \), the current density in the phosphor on the cathode side to the left of the sheet of charge as \( J_p \), the total insulator capacitance as \( C_i \), and making the following identifications

\[
J_m = \frac{\partial q_e}{\partial t}, \quad J_p = \frac{\partial q_i}{\partial t}, \quad C_i = \frac{c_{i1} c_{i2}}{c_{i1} + c_{i2}}
\]

leads to the following expression for \( J_m \):

\[
J_m = \frac{C_i}{C_i + C_p} \left[ J_p + \left(1 - \frac{d_s}{d_p}\right) \frac{\partial q_{sc}}{\partial t}\right] + C_i \frac{\partial v_x}{\partial t},
\]

where \( C_i \) is the total capacitance of the ACTFEL stack. Now, factor \( J_p \) from the square bracket term in Eq. (10) and define a multiplication factor, \( m(t) \), associated with the creation of space charge as follows:

\[
m(t) = \frac{\partial q_{sc}}{\partial q_e} + 1.
\]

Substituting Eq. (11) into (10) results in

\[
J_m = \frac{C_i}{C_i + C_p} J_p \left[ 1 + \left(1 - \frac{d_s}{d_p}\right) (m(t) - 1)\right] + C_i \frac{\partial v_x}{\partial t}.
\]

Finally, from Eq. (12) and the definition of the measured (i.e., external) dynamic capacitance, we obtain

\[
C_m = \frac{J_m}{J_m} = \frac{C_i}{C_i + C_p} \frac{\partial q_e}{\partial v_x} \left[ 1 + \left(1 - \frac{d_s}{d_p}\right) (m(t) - 1)\right] + C_i.
\]

Equations (12) and (13) are the primary results of this analysis.

As a check on the validity of Eq. (12), note that in the absence of space charge generation [i.e., \( m(t) = 1 \)] Eq. (12) reduces to Eq. (2) of Ref. 11. Furthermore, in the absence of space charge generation Eq. (13) reduces to

\[
C_m = \frac{C_i}{C_i + C_p} \frac{\partial q_e}{\partial v_x} + C_i = \frac{C_i}{C_i + C_p} \left[ \frac{\partial q_e}{\partial v_x} + C_p \right].
\]

Note that
The ALE ZnS:Mn ACTFEL devices investigated in this work exhibit multiplication of the charge. The amount of multiplication is quite significant when the measured capacitance is to the actual, physical insulator capacitance depends on the extent to which the differentially applied voltage drops exclusively across the insulator, as indicated in the above relation for $C_i$ [i.e., Eq. (15)]. When all of the differential voltage drops across the insulator, a situation of perfect-field-clamping results.

Notice that the above expressions for $C_i$ and $C_m$ [i.e., Eqs. (14) and (15)] imply that in the absence of space charge generation the measured capacitance never exceeds the physical capacitance of the insulator layers.

From Eqs. (12) and (13), it is evident that the generation of space charge results in an increase in the measured external current and capacitance. The extent of the space charge perturbation of the electrical characteristics in contrast to what it would be ideally in the absence of space charge creation depends upon two things: how much space charge is created [given by $m(t)$] and the location in the phosphor where the space charge is generated (given by $d_s$). Space charge is most effective in increasing the measured current or capacitance if it is created near the cathode interface.

According to the analysis presented here, the CV over shoot is directly related to the multiplication of the charge concomitant with space charge generation. We can obtain an estimate of the extent of this electron multiplication by solving Eq. (13) for $m(t)$ to obtain

$$m(t) = \frac{d_p}{d_p - d_s} \left( \frac{C_m - C_i}{C_i + C_p} \right) \frac{\partial q_c}{\partial v_s} - 1 + 1.$$  

(16)

As a check of Eq. (16), note that $m(t) \rightarrow 1$ as $\partial q_c/\partial v_s \rightarrow C_i$ and $C_m \rightarrow C_i$ [i.e., under field-clamping conditions when the measured capacitance is identical to the physical insulator capacitance, there is no electron multiplication (i.e., space charge generation) in the phosphor]. Assuming that all of the space charge is created near the cathode interface (i.e., $d_s < d_p$) and that field-clamping conditions occur (i.e., $\partial q_c/\partial v_s \rightarrow C_i$), this gives $m(t) = 1.4$, 2.1, and 2.5 for the thin, normal, and thick ALE ZnS:Mn ACTFEL devices employed in this study. If it is assumed that the space charge is created at the center of the phosphor layer, these $m(t)$'s are 1.8, 3.2, and 4.0. Thus, all three of the ALE ZnS:Mn ACTFEL devices analyzed exhibit multiplication of the injected electron conduction current due to space charge generation. The amount of multiplication is quite significant for the thick ACTFEL device.

C. A possible origin of space charge

We believe that the origin of space charge generation in the ALE ZnS:Mn ACTFEL devices investigated in this work arises as a consequence of impact ionization of zinc vacancies present in the ZnS phosphor layer. The identification of the physical nature of space charge creation is a result of temperature-dependent electro-optic studies in which self-activated blue emission at 460 nm is detected at low temperatures by time-resolved luminescence measurements. Since this space charge identification is made via the detection of self-activated blue luminescence, it is more precise to attribute the impact ionization as being associated with self-activated luminescence centers where the self-activated center in our ACTFEL devices is a zinc vacancy-chlorine donor complex. Chlorine is identified as the coactivator which forms a complex with a zinc vacancy since the aluminum, zinc, and manganese ALE process gases which are used to fabricate the ACTFEL devices are all chlorides.

We believe that the ALE ZnS:Mn ACTFEL devices measured in this work exhibit a significant amount of space charge generation because of the incorporation of chlorine into the ZnS phosphor layer and that this chlorine incorporation leads to the creation of zinc vacancies via self-compensation. A simple thermodynamic assessment of zinc vacancy formation via self-compensation is now presented, following the approach of Ref. 13.

D. Thermodynamics of zinc vacancy formation in ZnS via self-compensation

The enthalpy of formation of an ionized vacancy is envisaged as the sum of the enthalpy of formation of a neutral vacancy and an electronic contribution which is related to the ionization energy of the vacancy:

$$\Delta H_f(V^z) = \Delta H_f(V^n) + \Delta H_f(V^e),$$  

(17)

where the superscript $z$ denotes the charge state of the vacancy and $x$ denotes the vacancy as being neutral. The thermodynamic stability of a semiconductor or insulator with respect to vacancy self-compensation is simply assessed by the condition

$$\Delta H_f(V^z) = 0$$  

(18)

which establishes a critical Fermi level position, denoted $E_F^{crit}$, beyond which it is more energetically favorable to create new, self-compensating vacancies rather than to modulate the Fermi level closer to the appropriate band edge.

An estimate for the ionization energies of a zinc vacancy in ZnS is indicated in Fig. 7. The enthalpy of formation of a fully ionized zinc vacancy in ZnS is given by

$$\Delta H_f(V^z_2) = \Delta H_f(V^z_2) + (E_{A1} - E_f) + (E_{A2} - E_f).$$  

(19)

The condition for self-compensation in ZnS via the creation of zinc vacancies is

$$\Delta H_f(V^z_2) = 0$$  

(20)

which leads to

$$E_F^{crit} = \frac{1}{2} \Delta H_f(V^z_2) + E_{A1} + E_{A2}.$$  

(21)

Substituting 2.87 eV for the enthalpy of the neutral vacancy and the ionization energies shown in Fig. 7 leads to

$$E_F^{crit} = 2 \text{ eV}.$$  

(22)
FIG. 7. A bulk energy band diagram of ZnS illustrating the estimated acceptor ionization energies of a zinc vacancy.

The implication of this analysis is as follows. As more chlorine donors are incorporated into the ZnS, the Fermi level is pushed towards the conduction band. This means that more donor electrons are ionized to the conduction band and, thus, increase the electron density in the phosphor. However, according to Eq. (22) when \( E_F > E_F^{th} \sim 2 \text{ eV} \), it is energetically more favorable to create a zinc vacancy (because of the "payback energy" of the donor electron falling from the "Fermi sea" to the acceptor ionization level)\(^{14}\) than to modulate the Fermi level any closer to the conduction band. This process of compensating shallow donors or acceptors via the creation of vacancies is referred to as self-compensation. According to the rather crude estimate given in Eq. (22), zinc vacancy creation via self-compensation is thermodynamically favorable when a moderate concentration of chlorine (or another donor) is present in the ZnS. Thus, space charge generation via impact ionization of zinc vacancies is invariably found\(^3,5-7\) in ALE ZnS:Mn ACTFEL devices which are grown using chlorine-containing process gases, whereas evaporated ZnS:Mn ACTFEL devices do not exhibit evidence of this kind of space charge generation.\(^3\)

E. Advantages and disadvantages of space charge generation

The primary experimental finding of this work is that the thicker the phosphor in an ALE ZnS:Mn ACTFEL device, the more space charge generation that occurs within the phosphor during device operation. Space charge generation is a mixed blessing. The primary disadvantage of the thicker ACTFEL devices is that the threshold voltage increases with increasing phosphor thickness, as is evident from Table I. However, there are two distinct advantages of having space charge generation occur during ACTFEL operation.

The first advantage has to do with the aging stability of ACTFEL devices with space charge generation. To see this, first consider the energy band diagram shown in Fig. 8 for a phosphor with no space charge (so that the slope of the energy bands is constant in the phosphor and insulator layers) which shows an electron in the phosphor conduction band impinging at the phosphor/insulator conduction band discontinuity. If there is indeed no space charge in the ZnS:Mn ACTFEL device, the phosphor field is constant with a magnitude of \(-1.75 \text{ MV/cm}\); thus, a significant number of the electrons which impinge upon the conduction band discontinuity are significantly heated. For these hot electrons to subsequently be trapped at interface states, they must dissipate a significant amount of thermalization energy to reach the bottom of the phosphor conduction band at the interface in addition to the energy that they must dissipate in the process of undergoing interface state trapping. Most of this energy is dissipated as phonons in a very thin region of the device near the interface. It is likely that such a localized phonon dissipation process would lead to local heating of the lattice and multiphonon emission\(^{17}\) such that interfacial interdiffusion occurs; this process of enhanced interdiffusion due to localized phonon dissipation has been proposed\(^{18}\) as an aging mechanism for evaporated ZnS:Mn ACTFEL devices.

In contrast to the no space charge, constant electric field case shown in Fig. 8, consider Fig. 9, in which space charge generation occurs and the electric field is not constant across the phosphor. In this case, the slope of the energy bands is large (i.e., a large electric field) near the cathode interface from where electrons are injected, but the energy bands are

FIG. 8. An energy band diagram for an ACTFEL device without any space charge in the phosphor layer.

FIG. 9. An energy band diagram for an ACTFEL device with space charge present in the phosphor layer.
rather flat (i.e., a small electric field) near the anode due to the creation of positive charge which arises from space charge generation. Thus, electrons which impinge at the anode phosphor/insulator interface are much cooler and dissipate much less thermal energy at the interface. Thus less interdiffusion and, hence, less aging is expected. Improved aging stability is indeed found for thicker ALE ZnS:Mn ACTFEL devices.

The second advantage of space charge is that although the threshold voltage does indeed increase with increasing phosphor thickness, the increase is not as large as it would be in the absence of space charge. To see this, return to Fig. 8 and recognize that as the thickness of the phosphor increases, the threshold voltage increases by the phosphor field times the additional thickness of the phosphor (assuming field-clamping occurs in the phosphor). In contrast, an analysis of Fig. 9 reveals that the increase in the threshold voltage with increasing thickness of the phosphor is equal to the average phosphor field times the additional thickness of the phosphor; note that when space charge generation occurs, the average field, as shown in Fig. 9, may be significantly less than that of the constant field in the absence of space charge generation, as illustrated in Fig. 8. Thus, although a threshold voltage penalty must be paid in order to increase the phosphor thickness, the penalty is less severe in the case when space charge is present in the phosphor. It is highly desirable to increase the phosphor thickness since an increased phosphor thickness leads to a corresponding increase in brightness.

IV. CONCLUSIONS

An electrical characterization study of ALE ZnS:Mn ACTFEL devices as a function of the thickness of the phosphor layer is presented. The primary result of this study is that the amount of space charge which is generated in the phosphor layer during ACTFEL device operation increases as a function of increasing phosphor thickness. This conclusion is deduced from experimentally determined trends in the C-V and Q-Fp characteristics. The origin of one manifestation of space charge generation (i.e., C-V overshoot) is quantitatively modeled using a single sheet charge model. Space charge generation is attributed to impact ionization of zinc vacancies which are constituents of chlorine-zinc vacancy self-activated complexes. A thermodynamic explanation for the existence of zinc vacancies in chlorine-doped ZnS due to self-compensation is offered. Finally, two advantages of space charge generation are described, namely, improved aging stability and a reduced threshold voltage increase with increasing phosphor thickness.

ACKNOWLEDGMENTS

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