AN ABSTRACT OF THE THESIS OF

John C. Hitt for the degree of Master of Science in Electrical and Computer Engineering presented on August 15, 1997.

Title: Static Space Charge in Evaporated ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices

Abstract approved: ____________

John F. Wager

The operation of alternating-current thin-film electroluminescent (ACTFEL) devices may be strongly affected by the presence of dynamic or static space charge in the phosphor layer during device operation. Dynamic space charge is a positive space charge which is periodically created and annihilated in the phosphor layer during each cycle of the applied voltage waveform. Static space charge is a positive space charge which, once created, essentially remains in the phosphor layer throughout the subsequent operation. The accomplishments presented in this thesis are the development of a method for estimating the density of static space charge in evaporated ZnS:Mn ACTFEL devices by comparing the average phosphor field under field-clamping conditions. The results presented indicate that the static space charge density for evaporated ZnS:Mn ACTFEL devices is approximately 7.7-14.4 mC/cm³ which corresponds to an ionized trap density of 4.8-9.0 × 10¹⁶ cm⁻³. Also presented is evidence that the phenomenon known as relaxation charge is a bulk effect, as it scales with the phosphor thickness, and also that overshoot in transferred charge measurements is largely due to overshoot in the relaxation charge. Finally, a novel transferred charge technique is presented in which the ACTFEL sample is electrically reset to the same starting conditions in terms of polarization charge and field prior to the measurement of the transferred charge. These electrically reset transferred charge measurements show different characteristics than the standard transferred charge characteristics, most notably in the lack of overshoot.
Static Space Charge in Evaporated ZnS:Mn Alternating-Current
Thin-Film Electroluminescent Devices

by
John C. Hitt

A THESIS
submitted to
Oregon State University

in partial fulfillment of the
requirements for the degree of

Master of Science

Completed August 15, 1997
Commencement June 1998
I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.
ACKNOWLEDGEMENTS

I would like to thank Dr. John Wager for his support, encouragement and tremendous enthusiasm during the course of the work leading up to the writing of this thesis.

I would also like to thank Paul Keir for his assistance and Sey-Shing Sun of Planar America for providing the evaporated ZnS:Mn samples used in this thesis.

Finally, I would like to thank my mother and father who made all of this possible in the first place.

This work was supported by the U.S. Army Research Office under contract DAAH04-94-G-0324 and by the Advanced Research Projects Agency under the Phosphor Technology Center of Excellence, Grant No. MDA 972-91-1-0030.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
<th>1 Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>ACTFEL Device Operating Basics and Literature Review</td>
</tr>
<tr>
<td>2.1</td>
<td>Device Structure and Fabrication</td>
</tr>
<tr>
<td>2.2</td>
<td>Ideal Device Operation</td>
</tr>
<tr>
<td>2.3</td>
<td>Space Charge Creation Mechanisms</td>
</tr>
<tr>
<td>2.4</td>
<td>Literature Review</td>
</tr>
<tr>
<td>2.5</td>
<td>Discussion and Summary</td>
</tr>
<tr>
<td>3</td>
<td>Electrical Characterization and Standard Measurement Techniques</td>
</tr>
<tr>
<td>3.1</td>
<td>ACTFEL Sample Electrical Preparation</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Sample Aging Requirements</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Sample Aging Methods</td>
</tr>
<tr>
<td>3.2</td>
<td>Experimental Setup</td>
</tr>
<tr>
<td>3.3</td>
<td>Characterization Methods</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Capacitance versus Voltage (C-V) Measurements</td>
</tr>
<tr>
<td>3.3.2</td>
<td>External Charge versus Voltage (Q-V) Measurements</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Internal Charge versus Phosphor Field (Q-F_p) Measurements</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Maximum Charge versus Maximum Applied Voltage (Q_{max} - V_{max}) Transferred Charge Measurements</td>
</tr>
<tr>
<td>3.4</td>
<td>Discussion and Summary</td>
</tr>
<tr>
<td>4</td>
<td>Experimental Results</td>
</tr>
<tr>
<td>4.1</td>
<td>Internal Charge versus Phosphor Field Analysis</td>
</tr>
<tr>
<td>4.2</td>
<td>Static Space Charge Density Determination</td>
</tr>
<tr>
<td>4.3</td>
<td>Transferred Charge Derivative Overshoot Characteristics</td>
</tr>
<tr>
<td>4.4</td>
<td>Electrically Reset Transferred Charge Measurements</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.5 Conclusions</td>
<td>46</td>
</tr>
<tr>
<td>5 Conclusions and Recommendations for Future Research</td>
<td>47</td>
</tr>
<tr>
<td>5.1 The Measurement of Static Space Charge Density</td>
<td>47</td>
</tr>
<tr>
<td>5.2 Transferred Charge Derivative Curve Overshoot</td>
<td>48</td>
</tr>
<tr>
<td>5.3 Electrically Reset Transferred Charge Measurements</td>
<td>51</td>
</tr>
<tr>
<td>Bibliography</td>
<td>52</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>ACTFEL device structure.</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Bipolar waveform pulse sequence.</td>
<td>5</td>
</tr>
<tr>
<td>2.3</td>
<td>Energy band diagram at flat band.</td>
<td>6</td>
</tr>
<tr>
<td>2.4</td>
<td>Energy band diagram for a positive voltage pulse.</td>
<td>7</td>
</tr>
<tr>
<td>2.5</td>
<td>Energy band diagram for the period immediately following the positive voltage pulse.</td>
<td>8</td>
</tr>
<tr>
<td>2.6</td>
<td>Energy band diagram for a negative voltage pulse.</td>
<td>8</td>
</tr>
<tr>
<td>2.7</td>
<td>Energy band diagram showing band bending effects due to space charge.</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>Experimental Setup</td>
<td>15</td>
</tr>
<tr>
<td>3.2</td>
<td>C-V family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer.</td>
<td>17</td>
</tr>
<tr>
<td>3.3</td>
<td>Q-V family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer.</td>
<td>18</td>
</tr>
<tr>
<td>3.4</td>
<td>Q-F_p family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer.</td>
<td>21</td>
</tr>
<tr>
<td>3.5</td>
<td>Standard transferred charge measurements for a ZnS:Mn ACTFEL sample with a 950 nm phosphor thickness.</td>
<td>23</td>
</tr>
<tr>
<td>4.1</td>
<td>Q-F_p curve for a ZnS:Mn ACTFEL device with a phosphor thickness of 900 nm.</td>
<td>26</td>
</tr>
<tr>
<td>4.2</td>
<td>Internal charge - phosphor field curves for three ACTFEL samples taken at 20, 40, and 60 V above threshold.</td>
<td>31</td>
</tr>
<tr>
<td>4.3</td>
<td>Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 300 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>36</td>
</tr>
<tr>
<td>4.4</td>
<td>Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 490 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>36</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>4.5.</td>
<td>Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 950 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>37</td>
</tr>
<tr>
<td>4.6.</td>
<td>Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 300 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>40</td>
</tr>
<tr>
<td>4.7.</td>
<td>Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 490 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>40</td>
</tr>
<tr>
<td>4.8.</td>
<td>Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 950 nm, driven at frequencies of 100, 1000, and 3000 Hz.</td>
<td>41</td>
</tr>
<tr>
<td>4.9.</td>
<td>Electrical reset procedure.</td>
<td>43</td>
</tr>
<tr>
<td>4.10.</td>
<td>Electrically reset transferred charge measurements for an evaporated ZnS:Mn sample with phosphor thickness of 950 nm.</td>
<td>44</td>
</tr>
<tr>
<td>4.11.</td>
<td>Electrically reset relaxation charge derivative curves for an evaporated ZnS:Mn sample with phosphor thickness of 950 nm.</td>
<td>46</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Experimentally determined steady-state field, $F_{ss}$, as a function of phosphor thickness</td>
<td>32</td>
</tr>
<tr>
<td>2.</td>
<td>Experimentally estimated cathode and anode fields as a function of phosphor thickness for three evaporated ZnS:Mn ACTFEL devices.</td>
<td>34</td>
</tr>
<tr>
<td>3.</td>
<td>Experimentally estimated threshold space charge density as a function of phosphor thickness for three evaporated ZnS:Mn ACTFEL devices operated at 1000 Hz.</td>
<td>38</td>
</tr>
</tbody>
</table>
Static Space Charge in Evaporated ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices

Chapter 1
Introduction

Electroluminescence is the generation of light through the application of an electric field to a substance. The discovery of this effect is credited to the physicist Destrieu [1] who in 1936 observed that light was emitted from powdered zinc sulfide (ZnS) when a large electric field was applied. Initially, there was some research into the use of powders in electroluminescence. However, electroluminescent devices fabricated using powdered phosphor layers exhibited short lifetimes and did not have the stability necessary for commercial applications. With the advent of suitable thin-film technology, the research shifted to thin-film electroluminescence (TFEL).

Most current TFEL devices employ bipolar waveforms, meaning that the applied voltage is positive for some portion of the waveform and negative for some portion of the waveform. When the TFEL devices require this type of driving waveform for proper operation, the device type is usually specified as alternating-current thin-film electroluminescence (ACTFEL). A very simplistic description of ACTFEL device operation which shows the necessity of a bipolar applied voltage waveform is as follows. When a voltage pulse of sufficient amplitude is applied to the device, electrons trapped at the cathodic interface are tunnel-emitted and are transported to the anodic interface. Due to this transfer of charge, a field is established which inhibits further tunnel emission of electrons from the cathodic interface. Thus, if a unipolar pulse is used, the voltage amplitude required for further electron tunnel emission would be excessively high. However, the field established by the transfer of electrons also has the effect of enhancing the cathodic field on a subsequent applied voltage pulse of opposite polarity.

The first commercial ACTFEL devices used zinc sulfide doped with manganese (ZnS:Mn). ZnS:Mn ACTFEL devices emit light with a yellowish color. In the mid
1980's three companies, Planar Systems, Sharp, and Finlux, introduced 9 inch diagonal flat panel displays using ZnS:Mn [2]. Since then, flat panel displays using ACTFEL technology have become one of the commercial flat panel display technologies, along with the dominant flat panel display technology, liquid crystal displays (LCD).

ACTFEL devices have some major advantages over LCD devices. LCD devices typically have a limited viewing angle which forces the user to look almost directly at the screen. ACTFEL devices can be manufactured with a viewing angle greater than 160°. In addition, ACTFEL devices tend to be much more durable in harsh conditions such as extreme temperatures and much less sensitive to mechanical shocks. The drawbacks of ACTFEL devices for flat panel display applications are that they require high voltages (typically about 200 V) in order to operate and are also rather inefficient, in terms of their quantum efficiency.

Space charge in ACTFEL phosphors has been a topic of recent research. The effect of a positive space charge in the phosphor layer is to enhance the field at the cathodic interface of the device, which in turn leads to enhanced tunnel injection of electrons from interface states. This enhancement of the cathodic field also allows the tunnel injection of electrons from interface states to occur at lower voltages than would otherwise be necessary. The process by which this space charge is created is yet to be resolved. Some concepts involve either hole creation through band-to-band impact ionization and subsequent hole capture, or field emission from shallow traps as the forming mechanism. Evidence presented in this thesis indicates that the majority of the space charge which exists in these devices, if not all of the space charge, is created prior to the threshold voltage. This evidence casts some doubt on the band-to-band impact ionization and subsequent hole capture theory as the field necessary for band-to-band impact ionization may not be achieved below the threshold voltage.

The focus of the research presented in this thesis is to solidify and expand knowledge of space charge in ZnS:Mn ACTFEL devices and to explore its effects on device operation. The thesis organization is as follows. Chapter 2 presents an overview of
ACTFEL device operation and a review of previously published literature relating to space charge in ACTFEL devices. Chapter 3 describes the measurement techniques and data presentation methods. Chapter 4 presents the theory and results used for the experimental determination of static space charge density. Also presented in Chapter 4 is a novel transferred charge measurement technique. Finally, Chapter 5 presents conclusions and recommendations for future work.
Chapter 2
ACTFEL Device Operating Basics and Literature Review

This chapter contains information regarding ACTFEL device operating fundamentals. Also, the literature regarding space charge in the phosphor layer is discussed.

2.1 Device Structure and Fabrication

The structure of the ACTFEL devices tested for this thesis is shown in Fig. 2.1. The fabrication begins with a glass substrate upon which indium tin oxide (ITO) is deposited. ITO is selected to act as the bottom conductor due to its high conductivity and also because it is transparent to light in the visible spectrum. After the ITO is deposited, an insulating layer of silicon oxynitride (SiON) is sputtered for the bottom insulator. SiON is used since it has a high breakdown field. The zinc sulfide (ZnS) layer is deposited next through vacuum evaporation. This zinc sulfide layer is doped with manganese to give ZnS:Mn. The purpose of the manganese dopant is to provide luminescent centers which emit photons when excited by electrons. The top insulator, SiON, is deposited next by sputtering. Finally, the top contact, aluminum (Al) is deposited by evaporation.

2.2 Ideal Device Operation

For this thesis, the driving waveform consists of a trapezoidal bipolar pulse sequence, as shown in Fig. 2.2. The letters A through J are used to label specific points on this driving waveform. The letter A represents the leading edge of the positive pulse. The letter B labels the point on the leading edge of the positive waveform where electrons begin to tunnel from the interface and the device is said to turn-on. Letters C and D represent the beginning and ending of the portion of the waveform during which the voltage reaches its maximum value. Finally, the letter
<table>
<thead>
<tr>
<th>Layer</th>
<th>Material/Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Electrode</td>
<td>Al (200 nm)</td>
</tr>
<tr>
<td>Top Insulator</td>
<td>SiON (110 nm)</td>
</tr>
<tr>
<td>Phosphor</td>
<td>ZnS:Mn (300, 490, 950 nm)</td>
</tr>
<tr>
<td>Bottom Insulator</td>
<td>SiON (180 nm)</td>
</tr>
<tr>
<td>Bottom Electrode</td>
<td>ITO (300 nm)</td>
</tr>
<tr>
<td>Glass Substrate</td>
<td>Corning 7059 Glass (1.1 mm)</td>
</tr>
</tbody>
</table>

**Figure 2.1.** ACTFEL device structure.

**Figure 2.2.** Bipolar waveform pulse sequence. The letters A through J represent specific points on the waveform which correspond to points on the measurements.
Figure 2.3. Energy band diagram at flat band.

E represents the end of the positive bipolar pulse. The negative pulse is similarly labelled.

The general theory of ACTFEL device operation is that when the driving waveform reaches the turn-on voltage, electrons stored at the phosphor-insulator interface are tunnel-emitted into the phosphor conduction band and drift across the phosphor layer. Some of these electrons may gain sufficient energy from the phosphor field to impact-excite luminescent impurities into excited states. When the luminescent impurities in the excited states relax back to their ground state, photons may be emitted. Finally, the tunnel-emitted electrons drift to the other interface where they are trapped at interface states. The next pulse, being of the opposite polarity, causes these electrons to be emitted and travel in the other direction.

Perhaps the best method of illustrating the processes involved in the emission and drift of electrons is through the use of energy band diagrams. The energy band diagram representation of the ACTFEL structure described in the previous section is shown in Fig. 2.3 for the flat-band case. Note the polarity of the driving waveform is with respect to the aluminum electrode.
Figure 2.4. Energy band diagram for a positive voltage pulse. Labels represent (a) electron tunnel emission from the interface, (b) impact excitation, (c) excitation and de-excitation, and (d) electron trapping at the anodic interface.

Figure 2.4 shows an energy band diagram representation of the positive pulse. The following events are illustrated: (a) electron tunnelling from the interface, (b) impact excitation of a luminescent center, (c) relaxation of the luminescent center and emission of a photon, and (d) collection of the tunnel-emitted electron at the opposite interface.

Figure 2.5 shows the state of the ACTFEL device during the time period between the positive and negative pulses. Illustrated in this figure is the leakage (emission) of an electron trapped in an interface state close to the conduction band back into the phosphor layer. The electron may either (a) drift back to the opposite interface, or (b) recombine with an ionized trap in the phosphor layer. The electrons trapped at the interface in excess of those trapped for the flat-band case, which constitute the polarization charge \((Q_{pol})\), give rise to an electric field in the phosphor called the polarization field \((F_{pol})\). This internal field results in a lower turn-on voltage for the negative applied voltage pulse as it acts in the same direction.
Figure 2.5. Energy band diagram for the period immediately following the positive voltage pulse. Illustrated is an electron emitted as "leakage" current. This electron can (a) drift to the opposite interface, or (b) recombine with some ionized trap.

Figure 2.6. Energy band diagram for a negative voltage pulse. Labels represent (a) electron tunnel emission from the interface, (b) impact excitation, (c) excitation and de-excitation, and (d) electron trapping at anodic interface.
2.3 Space Charge Creation Mechanisms

The existence of space charge within the phosphor results in an electric field which is dependent upon position. This is represented in an energy band diagram by a bending of the bands, as shown in Fig. 2.7. Space charge can be beneficial as it provides for a reduction in the phosphor field near the anode interface and an increase in the cathode field, as compared to the case of a similar applied voltage to a device with no space charge. These benefits are not without cost. As an electron traverses the phosphor layer, it is accelerated by a steadily weaker field. This results in a decrease in the impact excitation rate [3, 4].

Although the creation mechanism(s) which result in static space charge generation remain uncertain, there are two possibilities which seem most likely. The first is...
hole capture within the phosphor layer. Initially, a hole is generated by band-to-band impact ionization. Then it drifts due to the electric field until it is captured by a trap.

The second possible mechanism of static space charge generation is via the impact or field ionization of deep level traps. Impact ionization occurs when an electron in the conduction band acquires sufficient energy from the electric field and impact ionizes an electron in the trap. Rather than relax, the conduction band electron drifts with the electric field to the anodic interface. Field ionization involves the tunneling of a trapped electron to the conduction band or a trapped hole to the valence band.

2.4 Literature Review

The existence of space charge within the phosphor layer of ACTFEL devices is one of the more important deviations from the ideal or simplified device operating characteristics. This space charge can be described by either of two models, static or dynamic [5]. The model for static space charge is that it has a long lifetime with respect to the frequency of the driving waveform. Therefore, once it has been created, either through the impact ionization of deep level traps, or through hole trapping, it is thought to remain in the phosphor layer with a density which is relatively invariant with respect to time. The model for dynamic space charge is that it is created in the phosphor layer during the time period of the waveform for which conduction is occurring and is at least partially destroyed during the time period in which current is not flowing.

Howard[6] first used the concept of space charge to describe the hysteresis effect seen in the brightness versus voltage (B-V) characteristics of many ACTFEL devices of the time. In his model, he assumed that electron-hole pair production occurred through impact ionization of the host lattice. Some of the holes created in this fashion are captured by deep level traps, thus creating a positive space charge in the phosphor.

Probe layer measurements conducted by Marrello et al. [3] showed that the
excitation efficiency of luminescent centers in the phosphor layers of ZnS:Mn varies as a function of distance from the cathodic interface. These experiments were conducted using evaporated ZnS phosphor layers in which the doping of manganese was controlled by an independent source. Using this technique, devices were fabricated in which ZnS was grown with a thin layer of ZnS:Mn grown at different locations. These locations, which were deliberately placed offset from the center of the phosphor layer, created a situation in which the excitation efficiency was different for electrons sourced from the bottom interface as opposed to that of electrons sourced from the top interface. This can be explained through the existence of space charge within the phosphor layer due to the location dependence of the phosphor field which results.

Geoffrey and Bringuier [7] used transferred charge analysis at varying frequencies to show the existence of a positive static space charge. The experiment compared the conduction charge for an undoped ZnS ACTFEL sample and a ZnS:Mn ACTFEL sample. An enhancement of the transferred charge near the threshold voltage was attributed to static space charge. This enhancement of the transferred charge characteristics is described as overshoot in the transferred charge analysis of the next chapter.

The measurement of the density of static space charge in ZnS:Mn ACTFEL devices has been a recent topic of interest. Using a modified bipolar pulse waveform in which "erasing" pulses are inserted between the positive and negative trapezoidal pulses, Ohmi et al. were able to calculate a density of $7.3 \times 10^{16} \text{ /cm}^3$ for static space charge in ZnS:Mn ACTFEL devices.

In addition to the study of space charge density, modelling and simulation of its effects has also been a topic of research interest. Howard [8] was the first to simulate the hysteretic behavior of ZnS:Mn ACTFEL devices by considering the effects of space charge. Neyts et al. [9] built upon the model of Howard in their simulation approach. Using a single sheet model of the space charge, Keir et al. [10] were able to simulate the effects of dynamic space charge.
2.5 Discussion and Summary

This chapter describes the basic structure of the metal-insulator-semiconductor-insulator-metal (MISIM) stack ACTFEL device. The waveform used to drive the devices for the data presented in this thesis is described. Energy band representations of the device for the flat-band condition, the positive applied voltage pulse, the period following the positive pulse, and the negative pulse are described. Two deviations from ideal device behavior, band-to-band impact ionization and subsequent hole-trapping, and the ionization of deep level traps, are described as possible space charge forming mechanisms. Finally, a review of the relevant literature regarding space charge in ZnS phosphor layers is presented.
Chapter 3
Electrical Characterization and Standard Measurement Techniques

This chapter presents the procedures by which the ACTFEL samples are prepared for electrical characterization and also the electrical measurements commonly used. First, the need for sample aging is discussed along with the aging procedure. Second, the standard electrical characterization methods obtained by plotting transient signals are discussed. Finally, the standard transferred charge measurement techniques are described.

3.1 ACTFEL Sample Electrical Preparation

3.1.1 Sample Aging Requirements

The ACTFEL samples used for this thesis all have electrical characteristics which change as a function of the total time which they have been operated. This creates a problem for accomplishing electrical characterization since it is difficult, if not impossible, to separate the electrical characteristics of interest from these aging characteristics.

It is fortunate, however, that the rate of change of the electrical characteristics due to device aging slows dramatically after only a few hours of operation. It is, therefore, possible to age the samples to such an extent that aging effects can be neglected.

A correct aging procedure for these samples is one that meets the following specifications: 1) The samples must be in a testable condition after aging. 2) The samples must be aged to such an extent that they can be considered electrically stable. 3) The procedure must be easily repeatable.

The first condition above is met if the sample does not have burn-out marks after the aging procedure. For obvious reasons, if the device is partially burned-out,
the active area will be decreased and therefore, the electrical measurements, all of which are normalized with respect to area, will be affected.

The second condition, that the ACTFEL sample be electrically stable after aging, is met by aging for a long duration of time such that the device aging is negligible for the duration of subsequent testing. The steady-state measurements employed herein (C-V, Q-V, and Q-Fp) are accomplished in a matter of a few minutes. In contrast, transferred charge measurements may take up to an hour.

The third condition, that the aging procedure be easily repeatable, is simply a requirement for an automated procedure. This is necessary as in this thesis the electrical characteristics of three ACTFEL devices are compared which differ only in phosphor thickness.

3.1.2 Sample Aging Methods

Aging the ZnS:Mn sample correctly is more difficult than simply applying a waveform and waiting. This approach was tried initially but did not yield acceptable results as the devices exhibited many burn-out spots.

One aging procedure tried by a previous researcher was to age the device with a relatively high frequency sine wave at an elevated temperature [11]. The frequency used was on the order of 6 kHz and the temperature was 100°C. This method succeeded in stabilizing the sample electrical characteristics but left the device with more than a few burn-out marks.

The aging technique used for the samples in this thesis is to age the samples in a vacuum chamber with a large series resistance. The series resistance value used is about 3000 Ω and the house vacuum system is used, providing a vacuum pressure of about 175 torr. The ACTFEL device is then driven with the standard trapezoidal waveform at 1 kHz for three hours. This procedure yielded excellent results as samples aged using this procedure did not exhibit any noticeable burn-out spots and also were electrically stable.
3.2 Experimental Setup

The experimental set-up is shown in Fig. 3.1. A Wavetek model 395 arbitrary waveform generator is used to create the driving waveform with a maximum amplitude of 5 volts. A custom-built amplifier relying upon two Apex model PA-85 amplifiers and a switching network is used to amplify the output of the arbitrary waveform generator to a maximum amplitude of about 320 volts. The waveforms, one measured at the aluminum electrode of the device and the other at the sense capacitor are acquired using a Tektronix model TDS420A digitizing oscilloscope. Both the arbitrary waveform generator and the digitizing oscilloscope are connected to a personal computer through a GPIB interface.

The series resistor, $R_s$, serves two main purposes. The first is to limit the current that the amplifier would have to source should the device under test fail catastrophically into a short circuit. The second is to limit the current in the device while it is aging. In this case, the resistor value is selected to be about 3 k$\Omega$. Under measurement conditions, a 500 $\Omega$ resistor is used.

The sense capacitor is a polypropylene capacitor with a value of 103.9 nF. This
set-up, with a sense capacitor configured as shown in Fig. 3.1 is referred to as a Sawyer-Tower [12] configuration. The value selected for this capacitance should be about 100 times greater than the total unnormalized capacitance of the device to be tested, the devices tested in this thesis have total unnormalized capacitances of about 1 nF. A large sense capacitance is necessary in order for the majority of the applied voltage to be dropped across the ACTFEL sample tested rather than across the sense capacitor.

3.3 Characterization Methods

3.3.1 Capacitance versus Voltage (C-V) Measurements

The C-V [13] measurement is one of the easiest ACTFEL measurements to understand. The electrical data from the leading edge of either the positive or the negative applied voltage waveform is used. First, the current through the sense capacitor is calculated using:

\[ i_{ce}(t) = C_s \frac{dv_3(t)}{dt}. \]  

(3.1)

The current through the ACTFEL device is calculated using:

\[ i_{el}(t) = C_{el} \frac{d(v_2(t) - v_3(t))}{dt}. \]  

(3.2)

Equating the two currents, the capacitance of an ACTFEL device is calculated via

\[ C_{el} = C_s \frac{dv_3(t)}{d(v_2(t) - v_3(t))}. \]  

(3.3)

\( C_{el} \) is calculated for each point of the applied waveform. Once this is accomplished, \( C_{el} \) is plotted as a function of the applied voltage, \( v_A(t) \), given by

\[ v_A(t) = (v_2(t) - v_3(t)). \]  

(3.4)

Ordinarily only the data from the leading edge of the waveform is plotted. Note that Eq. 3.3 expresses the capacitance of the ACTFEL device without \( C_{el} \) being a
Figure 3.2. C-V family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer. These measurements are taken at 20, 40, and 60V above threshold with the arrow in the figure pointing in the direction of increased measurement voltage. Also shown are the physical insulator capacitance and physical total capacitance of the device.

In order to consider the static capacitance of the ACTFEL device, the equation for calculating current through the device would be modified as follows. For the case of a static capacitance as a function of applied voltage, \( C_{el}(v) \), the current is given by:

\[
i_{el} = \frac{d}{dt}[C_{el}(v)v_A(t)] = C_{el}(v) \frac{dv_A(t)}{dt} + v_A(t) \frac{dC_{el}(v)}{dv_A} \frac{dv_A}{dt}
\]  

(3.5)

Figure 3.2 shows C-V curves for a ZnS:Mn ACTFEL sample with a phosphor layer which is 900 nm thick generated using the positive voltage pulse. Note that the capacitance for the smaller voltages corresponds to the total capacitance of the device, \( C_t \), and after turn-on the capacitance corresponds to the insulator capacitance, \( C_i \).

An examination of Eqn. 3.1 and Eqn. 3.2 shows that both the derivative of the sense capacitor voltage and the derivative of the voltage across the ACTFEL device are necessary for the calculation of the capacitance \( C_{el} \). It has been suggested that
Figure 3.3. Q-V family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer. These measurements are taken at 20, 40, and 60 V above threshold with the inner Q-V curves being at the lower voltage.

perhaps the current-limiting resistor, $R_s$, could be used as a current sense resistor to eliminate one of these differentiations in order to provide a more noise-free C-V curve. This is not the case as the derivative of the applied voltage (i.e. $v_2(t) - v_3(t)$) requires the differentiation of both of the measured voltages.

3.3.2 External Charge versus Voltage (Q-V) Measurements

The Q-V measurement is also a very common characterization method for ACTFEL devices. A Q-V plot is obtained by plotting the charge measured on the sense capacitor, $q_{ext}$, normalized to the device area versus the voltage measured across the device, $v_A(t)$. The external charge is given by

$$q_{ext}(t) = C_s v_3(t). \quad (3.6)$$

Some of the important features of the Q-V curve are shown in Fig. 3.3. First, note that the A through J labels corresponding to the labels on the driving waveform (Fig. 2.2) and that the Q-V plot moves clockwise with respect to time. Starting from
point A and ending at point B, the slope of the Q-V curve should be equal to the total capacitance of the device. From point B to point C, the phosphor is conducting and is effectively shorted. This results in the slope of the curve from point B to point C being equal to the parallel combination of the two insulator capacitances. From point C to point D, the applied waveform is at its steady-state value and the increase in \( q_{ext} \) is due to what is termed relaxation charge. Finally, from point D to point E, the applied waveform decreases back to zero and the slope of the Q-V curve has a magnitude equal to the total capacitance of the device.

3.3.3 Internal Charge versus Phosphor Field (Q-F\(_p\)) Measurements

The Q-F\(_p\) measurement [14] is perhaps the most difficult to obtain correctly and to analyze. The measurement consists of plotting two internal quantities which are calculated from measured external quantities. In 1989, Bringuier published two equations which relate these internal quantities to the external voltages measured and the external charge. The equation for internal charge is

\[
q(t) = \frac{C_i + C_p}{C_i} q_{ext}(t) - C_p \left[ v_2(t) - v_3(t) \right]. \tag{3.7}
\]

The equation for phosphor field is

\[
f_p(t) = \frac{1}{d_p} \left( \frac{C_s v_3(t)}{C_i} - [v_2(t) - v_3(t)] \right) \tag{3.8}
\]

where \( d_p \) is the phosphor thickness.

It is the explicit dependence of the phosphor capacitance, \( C_p \), in the internal charge relation and its implicit dependence in the phosphor field relation that make obtaining an accurate Q-F\(_p\) difficult. For almost all ACTFEL devices, it is easy to accurately measure the total capacitance of the device. For most ACTFEL devices, however, it is difficult to accurately measure the insulator capacitance using the C-V or Q-V method. The Q-F\(_p\) plot exhibits curvature for the entire positive pulse and the entire negative pulse. An example of a Q-F\(_p\) curve is shown in Fig. 3.4.

Analysis of the Q-F\(_p\) curve is critical to the determination of static space charge density, as discussed in Chapter 4. Note that the A-J labels provided for the bipolar
pulse sequence in Chapter 2 are useful in an explication of a $Q-F_p$ curve. Starting at point A, the $Q-F_p$ moves counterclockwise as a function of time. In fact, what is seen from an examination of points A to B is that there is no change in the internal charge measured. This is expected as the charge is thought to move through the phosphor layer only after the turn-on field has been reached.

At point B, the device turns on. Concomitant with this turn-on is the movement of charge from one interface in the phosphor to the other. From points B to C, the field within the ACTFEL device is constant. This is called a steady-state field, $F_{ss}$. Figure 3.4 shows the $Q-F_p$ plots for three voltages above that of the threshold voltage. All three voltages exhibit the same steady-state field. This occurrence is called field-clamping in which the steady-state field is independent of the maximum applied voltage above threshold.

From point C to point D, the applied voltage is at its peak value. Charge which flows during this portion of the applied waveform is called relaxation charge as the phosphor field is seen to relax due to the movement of charge from one interface to the other.

From point D to point E, the applied waveform voltage drops to zero. The movement of charge across the phosphor layer stops and the phosphor field reverses due to the charge transferred from one interface to the other. From point E to point F, there is a decrease in the internal charge. This loss of charge is denoted as $Q^+_{leak}$, the leakage of the transferred charge of the positive pulse.

In the analysis of $Q-V$ curves, it is stated that the slope of the pre-turn-on region corresponds to the total capacitance of the ACTFEL device and that of the post-turn-on region corresponds to the insulator capacitance. Analysis of Eqns. 3.7 and 3.8 in conjunction with an analysis of the $Q-F_p$ curve yield a much more mathematically satisfying explanation. For the pre-turn-on region, note that there is no change in the internal charge. Thus, taking the time-derivative of Eqn. 3.7 and setting the left-hand-side equal to zero yields

$$0 = \frac{C_i + C_p}{C_i} \frac{dq_{ext}(t)}{dt} - C_p \frac{dv_A(t)}{dt}. \quad (3.9)$$
Figure 3.4. Q-F<sub>p</sub> family of curves for a ZnS:Mn ACTFEL sample with a 950 nm thick phosphor layer. The maximum applied voltages for these curves are 20, 40, and 60 V above threshold.

Separating the terms and multiplying through by C<sub>i</sub> yields

\[ (C_i + C_p) \frac{dq_{ext}(t)}{dt} = C_i C_p \frac{dv_A(t)}{dt}. \]  \hspace{1cm} (3.10)

Dividing both sides by (C<sub>i</sub>+C<sub>p</sub>) and \( \frac{dv_A(t)}{dt} \) yields

\[ \frac{dq_{ext}(t)}{dv_A(t)} = \frac{C_i C_p}{C_i + C_p}. \]  \hspace{1cm} (3.11)

Equation 3.11 shows that the slope of the Q-V curve in the pre-turn-on region is equal the total capacitance of the ACTFEL device. This is the case for almost all ACTFEL devices as internal charge conduction only occurs above the threshold field.

For the post-turn-on region, note that the phosphor field is constant if field-clamping occurs. Taking the time-derivative of Eqn. 3.8 and setting the left-hand-side equal to zero yields

\[ 0 = \frac{1}{d_p} \left( \frac{1}{C_i} \frac{dq_{ext}(t)}{dt} - \frac{dv_A(t)}{dt} \right). \]  \hspace{1cm} (3.12)

Multiplying each side by \( d_p \) and separating the terms yields

\[ \frac{1}{C_i} \frac{dq_{ext}(t)}{dt} = \frac{dv_A(t)}{dt}. \]  \hspace{1cm} (3.13)
Multiplying by $C_i$ and dividing by $\frac{dv_A(t)}{dt}$ yields

$$\frac{dq_{ext}(t)}{dv_A(t)} = C_i. \quad (3.14)$$

Equation 3.14 shows that the slope of the Q-V curve in the post-turn-on region will equal the total insulator capacitance of the ACTFEL device, provided that the phosphor field is time independent (i.e. clamped).

3.3.4 Maximum Charge versus Maximum Voltage ($Q_{\text{max}}$-V$_{\text{max}}$) Measurements

The $Q_{\text{max}}$-V$_{\text{max}}$ measurement provides a way to measure the electrical threshold of the ACTFEL device. The maximum charge (see Fig. 3.3) is measured and plotted against the applied voltage which is swept ordinarily from some voltage below threshold to about 60 V above threshold. Both the maximum internal charge ($Q_{\text{max}}$) and the maximum external charge ($Q_{\text{max}}^e$) can be plotted for this measurement.

The maximum external charge is obtained through an examination of the Q-V plot and is simply the peak value of the charge. Note that for a properly operating ACTFEL device, this point always occurs at point D on the applied voltage waveform. The maximum internal charge usually occurs at point D also. However, this is not always the case as certain ACTFEL devices exhibit some low field conduction, meaning that the internal charge continues to increase as the applied waveform decreases. For the samples tested in this thesis, it is assumed that the maximum of both the internal and external charge occurs at point D on the applied voltage waveform for the positive voltage pulse and at point I for the negative voltage pulse.

As shown in Fig. 3.5, the slopes of both the maximum internal charge and the maximum external charge curves are significant. The initial (pre-threshold) slope of the external charge is equal to the total capacitance of the device. The post-threshold slope of the external charge is equal to the insulator capacitance for an ideal ACTFEL device. Note that in the transition from pre- to post-threshold regions of operation, these ZnS:Mn ACTFEL devices exhibit overshoot. Previous researchers have attributed this overshoot to metastable hole trapping [11]. Their perspective
Figure 3.5. Standard transferred charge measurements for a ZnS:Mn ACTFEL sample with a 950 nm phosphor thickness. Shown are (a) the maximum external charge, (b) the maximum internal charge, (c) the derivative of the maximum external charge with respect to maximum applied voltage, and (d) the derivative of the maximum internal charge with respect to maximum applied voltage. All plots are for frequencies of 100, 1000, and 3000 Hz, as indicated on each figure.
is that holes formed through band-to-band impact ionization collect near the phosphor/insulator interfaces at metastable trapping sites which precludes interface state electrons from recombining with these holes. Since more interface state electrons are available in higher energy states than if interface hole trapping were not to occur, these electrons can tunnel at lower fields which results in an enhancement of electron transfer across the phosphor layer. While this explanation may seem plausible, an examination of the overshoot as a function of phosphor thickness, which is presented in Chapter 4, shows that the overshoot in the transferred charge derivative curves is a function of the thickness of the phosphor layer. This evidence indicates that the overshoot is a phosphor bulk effect.

Another explanation of the overshoot in the transferred charge derivative curves is that the formation of a static space charge in the phosphor layer is the cause. If this is the case, then the overshoot would in fact be a function of the phosphor layer thickness, as it in fact is. However, research into the average phosphor field at the threshold voltage indicates that the space charge which is believed to exist in the phosphor layer of evaporated ZnS:Mn ACTFEL devices is formed prior to reaching the threshold voltage. Also, an examination of the relaxation charge characteristics of these devices shows that most, if not all, of the overshoot in the transferred charge derivative curves is due to overshoot in the relaxation charge derivative curves.

3.4 Discussion and Summary

This chapter presents the electrical preparation techniques, the experimental set-up, and the characterization methods used for the assessment of ACTFEL devices. The steady-state data presentation techniques (C-V, Q-V, Q-Fp) are described with some emphasis placed on the Q-Fp method since it forms the basis for the determination of static space charge density, as discussed in Chap. 4. The transferred charge measurement, \( Q_{max} - V_{max} \), is also discussed.
Chapter 4
Experimental Results

This chapter presents the theory and results for the determination of static space charge density. Also presented are results from the standard transferred charge measurement, $Q_{\text{max}}^c-V_{\text{max}}$, which indicate that the overshoot seen in the transferred charge capacitance curve (i.e. $dQ_{\text{max}}^c/dV_{\text{max}}$) is most likely a phosphor bulk phenomenon as opposed to an interface phenomenon. Finally, a novel transferred charge technique is presented in which the ACTFEL device is reset to the same initial state prior to the measurement of the maximum charge.

4.1 Internal Charge versus Phosphor Field Analysis

In order to understand the determination of static space charge density and other information presented in this section, a detailed analysis of the Q-F$_p$ curve is necessary. Figure 4.1 shows a Q-F$_p$ curve for a ZnS:Mn ACTFEL sample with a phosphor layer thickness of 900 nm driven at 60 V above threshold. Note that the labels A through J correspond to special points of the driving waveform as shown in Fig. 2.2. Also note that many of the quantities which can be obtained from a Q-F$_p$ curve are explicitly indicated in Fig. 4.1. The intent of this section is to provide a brief description of each of these quantities such that a greater understanding of the terms used in this chapter is attained. First, note that for each quantity obtained during the positive applied voltage pulse, there is a corresponding quantity for the negative applied voltage pulse. Next, it is found that evaporated ZnS:Mn ACTFEL devices exhibit electrical characteristics which are symmetric with respect to the applied voltage polarity. This being the case, only the positive pulse is considered herein.

An automated system for measuring these transferred charge characteristics has been established using the experimental set-up described in the previous chapter.
Figure 4.1. $Q-F_p$ curve for a ZnS:Mn ACTFEL device with a phosphor thickness of 900 nm. Labels A - J correspond to special points of the driving waveform.

The automated system uses the offset and gated measuring features of the digitizing oscilloscope to acquire the necessary voltages at points A, C, D, and E of the applied voltage waveform and also the corresponding points on the negative waveform. The offset feature is used to shift the position of the measured voltage to the center of the dynamic range of the oscilloscope and allow the use of a fine voltage scale. The gated measurement feature of the oscilloscope allows estimation of the voltages at point C of the applied voltage waveform. It may seem that point C, being a well-defined point in time, would be easy to measure. It turns out, however, that due to the RC effects of the series resistance, that point C always occurs later in time than at the end of the rise time of the positive applied voltage pulse. It is also necessary to use the gated measurement feature to measure the voltages at point E. It is not necessary to use the gated measurement feature to measure the voltage at points A and D of the applied voltage waveform as these points always correspond to the minimum and maximum voltages of the entire waveform, respectively.

The voltage measured at point A of the applied voltage waveform yields the polarization charge which exists at the phosphor-insulator interface due to the negative...
applied voltage pulse, $Q_{pol}^-$. Ideally, $v_2(t = A)$ is zero and the sense capacitor voltage is small such that the voltage across the device is approximately zero. This allows Eq. 3.7 to be simplified and the polarization charge to be given by

$$Q_{pol}^- = \frac{C_i + C_p}{C_i} C_s v_3(t = A). \tag{4.1}$$

At point C of the positive applied voltage pulse, the driving waveform has reached its peak value. Any charge that is transferred across the phosphor layer from the time at which the applied voltage waveform has reached the peak value until the time at which the voltage starts falling is denoted relaxation charge. The phosphor field relaxes during this period, hence the name relaxation charge. At points C and D, the internal charges, $Q_{int}^C$ and $Q_{int}^D$, are given by

$$Q_{int}^C = \frac{C_i + C_p}{C_i} C_s v_3(t = C) - C_p[v_2(t = C) - v_3(t = C)], \tag{4.2}$$

and

$$Q_{int}^D = \frac{C_i + C_p}{C_i} C_s v_3(t = D) - C_p[v_2(t = D) - v_3(t = D)]. \tag{4.3}$$

Thus, the relaxation charge, $Q_{relax}^+$, is the difference

$$Q_{relax}^+ = Q_{int}^D - Q_{int}^C. \tag{4.4}$$

Note that the maximum internal charge, $Q_{max}^+$ is measured at point D on the positive applied waveform, although occasionally some ACTFEL samples exhibit a maximum internal charge which occurs at some point between points D and E. Samples which exhibit a maximum internal charge which occurs later in the positive applied voltage waveform than point D most likely have poor insulators and are rare. None of the ACTFEL samples tested for this thesis exhibit low-field conduction. From the expression for the internal charge, at point D, $Q_{max}^+$ is given by:

$$Q_{max}^+ = \frac{C_i + C_p}{C_i} C_s v_3(t = D) - C_p[v_2(t = D) - v_3(t = D)]. \tag{4.5}$$

The conduction charge, $Q_{cond}^+$, is a measure of the charge transferred across the phosphor layer from point A on the applied voltage waveform to point D. For evaporated ZnS:Mn ACTFEL samples, which possess an abrupt turn-on and do not
exhibit charge collapse, $Q_{\text{cond}}^+$ can be measured from any point between points A and B on the applied voltage waveform to any point between points D and E. For some ACTFEL samples a decrease in the internal charge measured between points D and E occurs, this is known as charge collapse. When charge collapse occurs it is necessary to measure conduction charge as the internal charge difference between points A and D. Charge collapse is most often attributed to a collapse of a space charge region in the phosphor layer during the trailing edge of the applied voltage waveform. From Fig. 4.1, it is evident that $Q_{\text{cond}}^+$ is given by

$$Q_{\text{cond}}^+ = Q_{\text{max}}^+ - Q_{\text{pol}}^-.$$  (4.6)

The internal charge measured at point E on the positive applied voltage pulse is used to calculate the leakage charge due to the positive pulse, $Q_{\text{leak}}^+$. Leakage charge is a transfer of charge which results from the internal polarization field which is established in the phosphor layer due to the conduction charge, $Q_{\text{cond}}^+$. The leakage charge is simply the change in the internal charge from point E to point F on the applied voltage waveform during the zero bias portion of the applied voltage waveform. Since $v_2(t=E)$ and $v_2(t=F)$ should ideally be zero, $Q_{\text{leak}}^+$ is given by:

$$Q_{\text{leak}}^+ = \frac{C_i + C_p}{C_i} C_s [v_3(t = E) - v_3(t = F)].$$  (4.7)

Finally, the steady-state field, $F_{\text{ss}}$, is the average phosphor field which exists in the device during the leading edge of the applied voltage waveform in which the applied voltage exceeds the turn-on voltage. This phosphor field is deemed a steady-state field if it is constant (or relatively constant) between points B and C. $F_{\text{ss}}$ is given by:

$$F_{\text{ss}} = \frac{1}{d_p} \frac{C_s v_3(B < t < C)}{C_i} - [v_2(B < t < C) - v_3(B < t < C)].$$  (4.8)
4.2 Static Space Charge Density Determination

Space charge can play a very important role in the operation of ACTFEL devices and is a topic of recent research interest. [4, 5, 7, 14, 15, 16, 17, 18, 19] There are two primary advantages to having positive space charge in the phosphor layer. The first is that the phosphor field at the cathodic interface is enhanced, which leads to a greater injection efficiency of electrons from interface states to the phosphor conduction band. A consequence of the enhancement of the cathode field is that the charge transfer which occurs for a specific applied voltage is greater than that which would be achieved if the phosphor had no space charge. The second advantage is that the phosphor field at the anodic interface is reduced compared to that of the average field, which leads to the cooler recombination of electrons into interface states when they reach the phosphor/insulator interface. Additionally, a reduced anode field means that it is much less likely for electrons to be injected into the insulator layers. A disadvantage of positive space charge in the phosphor layer is that the excitation efficiency is reduced for those luminescent centers nearest the anodic interface. [3]

It is useful to distinguish between two types of space charge which may exist in the phosphor layer. These types of space charge are designated as dynamic or static, [5] depending on their characteristics. Dynamic space charge is space charge which is formed during the time electrons are being transported across the phosphor layer and is annihilated before the next pulse is applied. Dynamic space charge has been identified as the cause of overshoot in the measured C-V [17, 18, 10, 19], Q-F_p [14], and current transient I(t) [16, 19] characteristics. Dynamic space charge has been found to play a role in the operation of atomic layer epitaxy (ALE) ZnS:Mn [5, 17, 18, 19] and SrS:Ce ACTFEL devices. For ALE ZnS:Mn devices, dynamic space charge is thought to be the result of the impact ionization of defect complexes involving a donor-acceptor pair and a zinc vacancy. [18, 19] For ALE SrS:Ce devices, dynamic space charge is thought to be the result of the impact ionization of Ce ions and as yet unidentified native defects. Static space charge is a positive space charge which, once created, remains in the phosphor layer throughout the subsequent operation of
the device. Static space charge has been identified as playing an important role in evaporated ZnS:Mn devices although its physical nature is not known at this time.

Note that the static/dynamic terminology for space charge arises from steady-state analysis techniques used to characterize ACTFEL devices. Dynamic space charge is evident from such steady-state measurements as C-V or Q-Fp analysis. The presence of static space charge, however, cannot be determined from a single steady-state measurement. Instead, a comparison of steady-state measurements must be conducted from which the presence of static space charge can be determined. It is important to note that the fundamental role of space charge, whether static or dynamic, is to modify the phosphor field such that the cathode field is enhanced and the anode field is reduced.

The samples used for this study consist of the standard ACTFEL structure as outlined in Chap. 2 with SiON top and bottom insulators and an evaporated ZnS:Mn phosphor layer. The top and bottom insulator thicknesses are 110 nm and 180 nm respectively, and the phosphor thicknesses are 300 nm, 490 nm, and 950 nm. The samples are aged as described in Sec. 3.1.2. Following the aging process, Q-Fp analysis is conducted using a 1 kHz trapezoidal waveform with 5 μs rise and fall times and a 30 μs pulse width. The voltages used for the Q-Fp [14] analysis are 20, 40, and 60 V above the individual threshold voltage for each sample tested. Subsequent analysis of the C-V and Q-V curves, along with the analysis of the Q-Fp curves shows no sign of dynamic space charge.

Figure 4.2 shows the Q-Fp curves for the positive applied voltage pulse for the three sample thicknesses each at 20 V, 40 V, and 60 V above threshold. Only the positive polarity is shown as the electrical characteristics of the evaporated ZnS:Mn ACTFEL samples tend to be symmetric. On the 20 V above threshold curve for the ACTFEL sample with a phosphor thickness of 950 nm, the labels A through D represent important points on the Q-Fp curve. The A to B portion of the Q-Fp curve, the applied voltage is ramping up but has not reached the level necessary for the tunnelling of electrons from the interface and their subsequent transport across
Figure 4.2. Internal charge - phosphor field curves for three ACTFEL samples taken at 20, 40, and 60 V above threshold. The samples thicknesses are: (a) 300 nm, (b) 490 nm, and (c) 950 nm. Note the thickness dependence of the steady-state field.
Table 1. Experimentally determined steady-state field, $F_{ss}$, as a function of phosphor thickness

<table>
<thead>
<tr>
<th>Phosphor Thickness (nm)</th>
<th>Steady-State Field (MV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.97</td>
</tr>
<tr>
<td>490</td>
<td>1.72</td>
</tr>
<tr>
<td>950</td>
<td>1.47</td>
</tr>
</tbody>
</table>

the phosphor layer. At point B, the turn-on voltage is reached and concomitantly electrons tunnel from the phosphor/insulator interface and are transported across the phosphor layer. At point D, the amplitude of the applied voltage has reached its maximum value and attains a steady-state value.

For the purposes of static space charge density determination, the B-C portions of the Q-$F_p$ curves shown in Fig. 4.2 are of importance as the steady-state field, $F_{ss}$, is estimated as the constant portion of the phosphor field between points B and C. Note also that for each sample tested, the steady-state field is independent of the applied voltage amplitude which indicates that field-clamping is occurring and that $F_{ss}$ corresponds to the clamping field. A summary of the experimentally deduced $F_{ss}$'s as a function of phosphor thickness is given in Table 4.2. An assessment of Fig. 4.2 indicates that $F_{ss}$ decreases as the phosphor thickness increases. This can be attributed to the change in the average phosphor field due to the existence of static space charge, with more static space charge present in the ACTFEL device with the thicker phosphor layer.

In order to estimate the static space charge density from these measured values of $F_{ss}$, two assumptions are necessary: (i) a uniform density of static space charge exists in the phosphor layer and (ii) the cathode field during the BC portion of the applied voltage waveform is a constant value which is independent of phosphor thickness. The second assumption is consistent with field-clamping within the ACTFEL
device which is exhibited for all three devices tested for this study. Given these two assumptions, an expression for the static space charge density may be derived as follows. First, find an expression for the phosphor field as a function of the distance away from the phosphor/insulator interface by integrating Poisson's equation,

\[ F_p(x) = F_p^{\text{cathode}} - \frac{1}{\epsilon_p} \int_0^x \rho dx' = F_p^{\text{cathode}} - \frac{\rho x}{\epsilon_p} \]  

(4.9)

where \( F_p^{\text{cathode}} \) is the phosphor field at the cathode phosphor/insulator interface, \( \epsilon_p \) is the phosphor dielectric constant, and \( \rho \) is the static space charge density. The measured average field, \( F_p \), may then be obtained by integrating Eq. 4.9 over the full thickness of the phosphor,

\[ F_p = \frac{1}{d_p} \int_0^{d_p} \left[ F_p^{\text{cathode}} - \frac{\rho x}{\epsilon_p} \right] dx = \frac{F_p^{\text{cathode}} - \frac{\rho d_p}{2\epsilon_p}}{d_p} \]  

(4.10)

where \( d_p \) is the thickness of the phosphor layer. If \( F_{ss} \) is identified as the average field under field-clamping conditions and it is recognized that the cathode field is constant when field-clamping occurs, an estimate of the static space charge density, \( \rho \), may be obtained from the use of Eq. 4.10 by measuring \( F_{ss} \) for two ACTFEL devices with differing phosphor thickness. Explicitly, this static space charge density estimate is given by

\[ \rho = \frac{2\epsilon_p (F_{ss}^{d_p2} - F_{ss}^{d_p1})}{d_{p1} - d_{p2}} \]  

(4.11)

The use of Eq. 4.11 and the experimental results collected in Table 4.2 leads to static space charge estimates of 7.7-14.4 mC/cm² or an ionized trap density of 4.8-9.0 \( \times 10^{16} \) cm\(^{-3}\). The 7.3 \( \times 10^{16} \) cm\(^{-3}\) static space charge density estimate of Ohmi et al. [5] is within the range of this estimate. Moreover, this estimate is comparable to the 5.0 \( \times 10^{16} \) cm\(^{-3}\) experimental value of the trapped hole concentration deduced by Howard et al. [6] in their analysis of the hysteretic behaviour of ZnS:Mn ACTFEL devices. Although Ohmi et al. [5] and the ACTFEL samples used for this thesis do not exhibit brightness-voltage hysteresis, it seems likely that the hole trapping mechanism proposed by Howard et al. [6] could be the origin of static space charge.

Using a static space charge density of 7.0 \( \times 10^{16} \) cm\(^{-3}\) (the average value estimated in this thesis), it is possible to calculate the cathode field (which is assumed
Table 2. Experimentally estimated cathode and anode fields as a function of phosphor thickness for three evaporated ZnS:Mn ACTFEL devices.

<table>
<thead>
<tr>
<th>Phosphor Thickness (nm)</th>
<th>Cathode Field (MV/cm)</th>
<th>Anode Field (MV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>490</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>950</td>
<td>2.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

constant, consistent with field-clamping) and the anode field as a function of phosphor thickness using Eqs. 4.9 and 4.10. These anode and cathode field values are collected in Table 4.2.

Two important points should be noted with respect to Table 4.2. First, the 2.2 MV/cm estimate of the cathode clamping field is higher than previous estimates. This is not surprising as previous estimates relied on the measured average field without considering the effect of static space charge in the phosphor layer. An important consequence of this larger estimate of the cathode clamping field is that the energy depth of the interface states responsible for field clamping are deeper than previously thought. For example, if the interface state emission of electrons into the conduction band is assumed to occur due to direct tunneling from an interface state density of $5.0 \times 10^{13}$ cm$^{-2}$ modeled as a Dirac well, the depth of the interface state is estimated to be 1.1 eV and 1.5 eV for cathode phosphor fields of 1.5 MV/cm and 2.2 MV/cm respectively (these estimates are based upon assuming a conduction band relative effective mass of 0.18 [20] and a threshold current density of 10 mA/cm$^2$).

The second important point with respect to Table 4.2 is the fact that the anode field during field-clamping is significantly smaller than the average field especially for the thicker devices. This is a desirable effect as it leads to cooler electron recombination at the anodic interface and precludes electron injection into the insulator. Both of these effects may contribute to ACTFEL aging but would be reduced in a device
with positive space charge in the phosphor layer as opposed to a similar device with no positive space charge in the phosphor layer.

4.3 Transferred Charge Derivative Overshoot Characteristics

As mentioned in Chapter 3, the initial explanation of overshoot in transferred charge measurements is that metastable hole traps exist at the interfaces which prevent trapping with some of the transferred interface state electrons at lower interface state energies. This explanation implies that the charge transferred in excess of that expected is the result of the transfer of these metastable electrons from higher energy interface states. If this is the case, then the overshoot should be independent of the phosphor layer thickness.

Bringuier [21] first noted that it is necessary to account for so-called "slow-hole trapping" when running numerical simulations of ACTFEL devices. It is thought that holes are generated near the cathodic interface through the process of band-to-band impact ionization. These holes are subsequently trapped as they drift across the phosphor layer. Although due to the high field involved (i.e. average phosphor fields are 1.5-2.0 MV/cm) this may seem to be an unlikely explanation, however, there is experimental evidence of bulk hole trapping at very high fields.[8, 16, 9, 4]

A comparison of the magnitude of overshoot for the three samples used in the experimental determination of the density of the static space charge presented in the previous section shows that the overshoot is a strong function of sample thickness. Figures 4.3, 4.4, and 4.5 show the derivative of the transferred charge curves for ACTFEL samples with a 300 nm, 490 nm, and 950 nm phosphor thickness, respectively, each taken at frequencies of 100, 1000, and 3000 Hz. Note that the overshoot for any specific frequency is a function of the device thickness and that the overshoot is largest for the thickest device.

An examination of the transferred charge derivative curves can yield important information. In the pre-threshold region, the derivative of the transferred charge curve very precisely yields the total capacitance of the ACTFEL device. In the
Figure 4.3. Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 300 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.

Figure 4.4. Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 490 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.
Figure 4.5. Transferred charge derivative curves for an ACTFEL sample with a phosphor thickness of 950 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.

In the post-threshold region, for the ideal device, the derivative of the curve should yield the insulator capacitance provided that the charge transported across the phosphor layer is sufficient such that the phosphor can be considered to be effectively shorted. Note that the total capacitance and insulator capacitance are indicated in each of Figs. 4.3, 4.4, and 4.5. In Fig. 4.3, the overshoot for the 300 nm thick ACTFEL device occurs in a somewhat lazy fashion after the threshold voltage is reached. In Fig. 4.4, the overshoot for the 490 nm thick ACTFEL device occurs much more steeply than for the 300 nm device. Finally, for the thickest device, the overshoot is the steepest. Also note that the overshoot characteristics are frequency dependent. The highest frequencies give the steepest overshoot characteristics.

Another interesting point about the transferred charge derivative curves arises from a calculation of the internal phosphor field at the threshold voltage. If there is no space charge, then the average phosphor field should be on the order of 2.2 MV/cm. If some positive space charge exists in the phosphor layer, then the average
Table 3. Experimentally estimated threshold space charge density as a function of phosphor thickness for three evaporated ZnS:Mn ACTFEL devices operated at 1000 Hz.

<table>
<thead>
<tr>
<th>Phosphor Thickness (nm)</th>
<th>Threshold Voltage (V)</th>
<th>Threshold Field (MV/cm)</th>
<th>Threshold Space Charge Density (Traps per cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>140</td>
<td>1.85</td>
<td>$1.0 \times 10^{17}$</td>
</tr>
<tr>
<td>490</td>
<td>181</td>
<td>1.95</td>
<td>$4.6 \times 10^{16}$</td>
</tr>
<tr>
<td>950</td>
<td>208</td>
<td>1.48</td>
<td>$6.9 \times 10^{16}$</td>
</tr>
</tbody>
</table>

Field should be lower. The phosphor field at threshold, $F_{th}$, is given by

$$F_{th} = \frac{C_i}{C_i + C_p} \frac{V_{th}}{d_p}$$

where $V_{th}$ is the threshold voltage. Using Eq. 4.10 and Eq. 4.12, the space charge density at threshold, $\rho_{th}$, can be calculated as

$$\rho_{th} = (F_{cath} - \frac{C_i}{C_i + C_p} \frac{V_{th}}{d_p}) \frac{2\epsilon_p}{d_p} = (F_{cath} - F_{th}) \frac{2\epsilon_p}{d_p}$$

Assuming the cathode field to be 2.2 MV/cm, then the threshold space charge density can be calculated from the measured threshold voltage.

Table 4.3 lists the relevant information regarding the space charge density at threshold. From this information it is seen that static space charge apparently exists in the phosphor layer prior to the onset of electron tunneling from the phosphor/insulator interface and subsequent transport across the phosphor layer. This observation points to the possible existence of sub-threshold effects which contribute to the operation of ACTFEL devices. Recently it has been surmised that such sub-threshold effects could possibly be related to the latent image properties of ACTFEL displays [22].

It is interesting to speculate on the mechanism which creates this sub-threshold space charge. One possibility is that prior to threshold, a very small number of electrons are emitted from the phosphor/insulator interface and create holes through
band-to-band impact ionization. These holes are subsequently trapped in the phosphor layer where they form the static space charge. The transferred charge measurement is performed in such a way that the device is under an applied voltage below threshold for some time. If a very small number of electrons create a very small number of holes which are subsequently trapped over many cycles of the applied voltage waveform, it is possible that over time a significant amount of space charge would be formed. Alternatively, sub-threshold static space charge could arise from the ionization of trap states in the bulk ZnS phosphor layer via emission of a trapped electron to the conduction band; such trap electron emission could be accomplished via tunnelling, thermionic emission, or possibly even impact ionization. More work is required in order to understand the mechanisms responsible for the formation of sub-threshold static space charge.

An examination of the relaxation charge is also valuable in determining the nature of the overshoot in the transferred charge measurements. The relaxation charge is the charge which is transported across the phosphor layer when the applied voltage is at its maximum value.

Figures 4.6, 4.7, and 4.8 show the relaxation charge derivative curves for evaporated ZnS:Mn devices with phosphor thicknesses 300 nm, 490 nm, and 950 nm respectively. Note that as found for the transferred charge derivative curves, the amount of overshoot is a function of both frequency and phosphor layer thickness. As the maximum charge is dependent upon the relaxation charge, the transferred charge derivative curves are also dependent upon the relaxation charge derivative curves. Therefore, from the data shown in Figs. 4.3-4.8 it would appear that the overshoot in the relaxation charge derivative curves is a major contributing factor in the overshoot of the transferred charge derivative curves. In fact, from the data it appears that relaxation charge is responsible for all of the overshoot in the transferred charge derivative curves.
Figure 4.6. Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 300 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.

Figure 4.7. Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 490 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.
Figure 4.8. Relaxation charge derivative curves for an ACTFEL sample with a phosphor thickness of 950 nm, driven at frequencies of 100, 1000, and 3000 Hz. The arrow points in the direction of increasing frequency.

4.4 Electrically Reset Transferred Charge Measurements

Transferred charge analysis is one of the classical methods for characterizing an ACTFEL device. [2] Typically, it is accomplished by plotting the conduction charge (often denoted as $\Delta Q$) as a function of the maximum applied voltage. The advantage of this technique is that the conduction charge which is transported across the phosphor layer is a measure of the total charge which gives rise to luminance. One disadvantage of this technique is that the voltage derivative of this curve, $d\Delta Q/dV_{\text{max}}$, cannot readily be interpreted as a capacitance that can be compared to either the total or insulator capacitance of the ACTFEL device in either the pre- or post-threshold portion of the $d\Delta Q/dV_{\text{max}}$ curve. In order to meaningfully interpret transferred charge derivative curves in terms of total and insulator capacitances, the maximum external charge-maximum applied voltage ($Q_{\text{max}}^e-V_{\text{max}}$) measurements in which the external net charge located at the phosphor/insulator interface with respect to the neutral charge level ($Q_{\text{max}}^e$) is plotted as a function of the maximum applied voltage ($V_{\text{max}}$) must be employed. [21, 23, 11]
The purpose of this section of the thesis is to describe a new method for accomplishing transferred charge analysis of an ACTFEL device. The measurement is accomplished using an applied voltage waveform in which a large number of bipolar pulses with a constant $V_{\text{max}}$ above threshold (these voltages are referred to as setting pulses with amplitude $V_{\text{sp}}^{\text{max}}$) are inserted between measuring pulses with amplitudes $V_{\text{mp}}^{\text{max}}$. The maximum external charge, $Q_{\text{max}}^e$, is monitored as a function of $V_{\text{mp}}^{\text{max}}$. The purpose of the setting pulse sequence is to ensure that the polarization charge prior to the measuring pulse is the same for each measuring pulse maximum amplitude. The utility of this measurement is demonstrated via an analysis of the characteristics of evaporated ZnS:Mn devices.

In order to obtain a steady-state measurement of the maximum charge versus the maximum applied voltage, the device must be reset to some initial state prior to the pulse for which $Q_{\text{max}}$ is to be measured. This can be done optically or electrically. The focus of this section is to examine transferred charge characteristics using an electrical resetting procedure. This reset procedure is illustrated in Fig. 4.9. The measurement is accomplished using an applied voltage waveform in which a large number of bipolar pulses with a constant applied voltage above threshold are inserted between measuring pulses of variable $V_{\text{max}}$. The transferred charge is monitored only during the measuring pulse. The purpose of the constant amplitude pulses, which are referred to as setting pulses, is to ensure that the polarization charge is constant for each measurement of $Q_{\text{max}}$. Because the electrically reset transferred charge measurements are performed with a constant initial polarization charge, they tend to exhibit transferred charge characteristics closer to steady-state than the conventional transferred charge measurements.

Electrically reset transferred charge curves denoted $(Q_{\text{max}}^e-V_{\text{max}})^{sp}$, and electrically reset transferred charge derivative curves denoted $(dQ_{\text{max}}^e/dV_{\text{max}})^{sp}$, for an evaporated ZnS:Mn ACTFEL device are shown in Fig. 4.10 for three different setting pulse voltages: $(V_{\text{max}})^{sp} = 20, 40, \text{ and } 60 \text{ V above threshold}$. Note that a larger $(V_{\text{max}})^{sp}$ leads to a larger initial polarization charge; this leads to the observed downward shift of the $(Q_{\text{max}}^e-V_{\text{max}})^{sp}$ curve and the left-going shift of the $(dQ_{\text{max}}^e/dV_{\text{max}})^{sp}$
Figure 4.9. Electrical reset procedure. This figure illustrates the setting pulses followed by the measuring pulse. Note that for all of the measuring pulses illustrated, the setting pulse amplitude remains constant.
Figure 4.10. Electrically reset transferred charge measurements for an evaporated ZnS:Mn sample with phosphor thickness of 950 nm. Setting pulse voltages of 20, 40, and 60 V above threshold are used.
curve. Very little, if any, overshoot is present in the \((dQ_{\text{max}}/dV_{\text{max}})^{sp}\) curve. This is in contrast to the large amount of overshoot present in the standard \(dQ_{\text{max}}/dV_{\text{max}}\) curves as seen in Figs. 4.3, 4.4, and 4.5. Moreover, the pre-turn-on and post-turn-on capacitances shown in the derivative curves are in excellent agreement with the expected total and insulator physical capacitances. Thus, these \((dQ_{\text{max}}/dV_{\text{max}})^{sp}\) curves exhibit capacitance-voltage (C-V) characteristics much more ideal than the corresponding \(dQ_{\text{max}}/dV_{\text{max}}\) curves.

The primary difference between \((Q_{\text{max}}-V_{\text{max}})^{sp}\) and \(Q_{\text{max}}-V_{\text{max}}\) curves is that the long sequence of setting pulses allows the ACTFEL device to be reset back to the same starting polarization charge state at the onset of each measuring pulse. In other words, the initial position of the quasi-Fermi level at the beginning of the measuring pulse is identical for all of the measuring pulses. In contrast, in a conventional \(Q_{\text{max}}-V_{\text{max}}\) measurement, the initial position of the quasi-Fermi level at the beginning of the measured pulse is different for each measuring pulse since \(V_{\text{max}}\) (which is primarily responsible for determining the magnitude of the polarization charge and possibly the static space charge) progressively increases throughout the measurement such that \(Q_{\text{max}}^{e}\) is assessed at a different initial polarization and static space charge state. Thus, the electrically reset transferred charge measurement tends to be much closer to an ideal steady-state measurement than the standard transferred charge measurement.

In the previous section it is shown that the overshoot seen in the transferred charge derivative curves is almost entirely due to the overshoot in the relaxation charge derivative curves. Since there is little, if any overshoot in the electrically reset transferred charge derivative curves, it is expected that the electrically reset relaxation charge derivative curves would show little, if any overshoot. Figure 4.11 shows the electrically reset relaxation charge derivative curves for an evaporated ZnS:Mn sample with a phosphor layer thickness of 950 nm with setting pulse voltages of 20, 40, and 60 V above threshold. Note that while there is overshoot in these curves, it is reduced from the standard relaxation charge overshoot curves by a factor of about 10.
4.5 Conclusions

The results of the measurement of the static space charge density which exists in ZnS:Mn ACTFEL devices yields a value of about $7.0 \times 10^{16}$/cm$^3$. The nature of the overshoot seen in these devices is revealed by examining the relationship between the overshoot in the maximum external charge and the overshoot seen in examining the relaxation charge only. Also, it is shown that a significant amount, if not all, of the static space charge which exists in evaporated ZnS:Mn ACTFEL devices is formed before the threshold voltage is reached. The pre-threshold space charge creation mechanism is as yet undetermined. Finally, a novel transferred charge technique called the electrically reset transferred charge measurement is presented in which the ACTFEL device is electrically reset using constant amplitude pulses to the same initial state prior to the application of the pulse for which $Q_{\text{max}}$ is measured. It is seen that there is little or no overshoot in the electrically reset transferred charge measurements for either $Q_{\text{max}}$ or $Q_{\text{relax}}$. 

Figure 4.11. Electrically reset relaxation charge derivative curves for an evaporated ZnS:Mn sample with phosphor thickness of 950 nm. Setting pulse voltages of 20, 40, and 60 V above threshold are used. Note the reduced amount of overshoot.
Chapter 5
Conclusions and Recommendations for Future Research

There are three main achievements presented in this thesis. First, a method is developed for the measurement of the density of static space charge which exists in evaporated ZnS:Mn ACTFEL devices. Second, the overshoot in the transferred charge derivative curves is shown to scale with phosphor layer thickness, indicating that it is a bulk effect as opposed to an interface effect. Finally, a novel transferred charge measurement technique is described which yields results which are closer to ideal steady-state measurements than that found using standard transferred charge techniques.

5.1 The Measurement of Static Space Charge Density

The static space charge density discussion in Chapter 4 presents a method for calculating the density of static space charge in the phosphor layer of evaporated ZnS:Mn ACTFEL devices. The presence of static space charge in the phosphor layer of ACTFEL devices cannot be confirmed with a single steady-state measurement. Instead, two or more steady-state measurements must be compared in order to both infer that static space charge is present, and also to calculate its density. Dynamic space charge in the phosphor layer of ACTFEL devices is different from static space charge in that its presence can be confirmed from a single steady-state measurement. The signs of dynamic space charge include overshoot in the C-V curves and field overshoot in the Q-F_p curves. A comparison of the average fields in the phosphor layers of two or more devices of differing phosphor layer thickness yields a static space charge density for evaporated ZnS:Mn ACTFEL devices of about $7.0 \times 10^{16}$ ionized traps per cm$^3$.

- Dynamic Space Charge Density Determination: The methods used in this thesis for the determination of static space charge has limited usage for ACTFEL
devices with phosphor layers other than evaporated ZnS:Mn. Both a steady-state field and field-clamping must be observed in the ACTFEL devices for this method to work. Research should be conducted to develop a means of determining both the static and the dynamic space charge density for devices which exhibit dynamic space charge effects or do not exhibit field-clamping.

5.2 Transferred Charge Derivative Curve Overshoot

The overshoot which is evident in the transferred charge derivative curve previously was attributed to the so-called "slow-hole trapping" also known as metastable hole trapping. It was thought that holes created through band-to-band impact ionization would be transported across the phosphor layer to the cathodic interface where they would be trapped at interfacial traps. Their metastability affects the tunnel-emitted and band-to-band impact ionized electrons which are transported to that interface on the subsequent pulse of opposite polarity such that these electrons would not recombine with the metastable holes and would therefore be trapped at higher energy levels at the interface. This would result in interfacially trapped electrons which would tunnel-emit at lower fields and would contribute to an unexpected increase in the amount of charge transported across the phosphor layer. This explanation requires overshoot in the transferred charge derivative curves to be an interface-related phenomenon. If this is the case, the amount of overshoot seen should be relatively independent of the phosphor layer thickness. In Chapter 4, the overshoot in the transferred charge derivative curves is shown to increase with increasing phosphor layer thickness. This indicates that the phenomenon which creates the overshoot is most likely a bulk phenomenon. Also, it is important to note that the overshoot in the transferred charge derivative curves is also a strong function of the frequency at which the measurements are taken.

Initially, in writing this thesis, it was suspected that the overshoot could be a symptom of the formation of the static space charge which is known to exist in the phosphor layer. One of the effects of a positive static space charge in the phosphor
layer of ACTFEL devices is an enhancement of the phosphor field at the cathodic interface. Therefore, the effect of an increasing amount of static space charge as a function of the applied voltage would be an increasing phosphor field at the cathodic interface. This would result in an increase in the number of electrons which would be tunnel-emitted from the cathodic interface, as it is believed that the phosphor field at the cathodic interface is clamped at 2.2 MV/cm during the time period for which electrons are tunnel-emitting from this interface. More electrons would have to tunnel-emit and be transported across the phosphor layer in order to maintain a phosphor field at the cathodic interface of 2.2 MV/cm.

An examination of the effect of relaxation charge in the transferred charge measurements shows that the relaxation charge derivative curves exhibit overshoot which is both a function of the frequency of the driving waveform and also the thickness of the phosphor layer. Since the transferred charge derivative curves also exhibit overshoot which is a function of operating frequency and phosphor layer thickness, a comparison is called for. This comparison shows that the overshoot in the transferred charge derivative curves is almost identical to the overshoot in the relaxation charge derivative curves. Thus, the overshoot in the transferred charge derivative curves is almost entirely due to the overshoot in the relaxation charge derivative curves.

Finally, the other evidence which is presented in Chapter 4 related to the transferred charge derivative overshoot is a comparison of the average phosphor field at the threshold voltage. From this comparison, it is evident that the static space charge which exists in the phosphor layer of evaporated ZnS:Mn devices is formed entirely below threshold. If a device had no space charge present in the phosphor layer and the cathodic field necessary for electron tunnel-emission is 2.2 MV/cm, then it would be expected that the phosphor field at the threshold voltage would be 2.2 MV/cm. This is clearly not the case, as measurements show that the phosphor field at the threshold voltage is in fact almost equal to the phosphor field at voltages well above threshold. It is this information which contradicts the overshoot in the transferred charge derivative curves as being a manifestation of the formation of static space charge in the phosphor layer.
• Relaxation Charge Mechanisms: It is important to determine the nature of relaxation charge in ACTFEL devices. Relaxation charge most likely causes the overshoot seen in the transferred charge derivative curves. Recently, device physics ACTFEL simulations have indicated that it is the result of the re-emission of trapped holes in the phosphor layer and their subsequent transport to the cathodic interface.[24] This seems inconsistent with the fact that there is not enough static space charge present in the phosphor layer to account for all of the relaxation charge seen. Other researchers have speculated that the relaxation charge overshoot is due to a time constant involved with tunnel-emission from the cathodic interface. The phosphor layer thickness dependence of relaxation charge casts doubt on this hypothesis.

• Sub-Threshold Effects: An effort should be made to determine the creation mechanisms of the static space charge which exists in the phosphor layer of evaporated ZnS:Mn devices. The evidence clearly shows that the static space charge is almost entirely created below threshold. This may indicate that the formation mechanism is not hole capture as previously speculated, but may in fact be due to electron emission from relatively shallow traps (compared to interface-state trap depth) in the phosphor layer.

• Zero Pulse-Width Transferred Charge Measurements: An effort should be made to investigate the characteristics of the transferred charge curves when the ACTFEL sample is driven with an applied voltage waveform with no pulse width. Most likely, no overshoot would be seen in the transferred charge derivative curves as with no pulse width, there would be no relaxation charge. This experiment has been attempted, but the results are obscure due to a large amount of noise in the data.
5.3 Electrically Reset Transferred Charge Measurements

The standard method for conducting transferred charge measurements is not a true steady-state measurement as the polarization charge is a function of the applied voltage amplitude. The electrically reset transferred charge measurements presented in Chapter 4 are much closer to ideal steady-state measurements as the ACTFEL device is brought to the same polarization charge state prior to the application of an applied voltage pulse for which the transferred charge and relaxation charge are to be measured. The electrically reset transferred charge derivative curves exhibit very little, if any, overshoot. The electrically reset relaxation charge derivative curves exhibit overshoot which is much less than the overshoot in the standard relaxation charge derivative curves. This is an expected result as it is shown in the analysis of the overshoot in the standard transferred charge derivative curves that relaxation charge plays a major role.

- Materials Research: ACTFEL samples with phosphor layers other than ZnS:Mn should be examined using both the standard and the electrically reset transferred charge measurements. An emphasis should be placed on the role of relaxation charge in other materials, such as SrS:Ce.
BIBLIOGRAPHY


