

# ACTFEL DEVICE MODELING VIA SPICE

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## Introduction

Two models for the SPICE (Simulation Program with Integrated Circuit Emphasis) simulation of alternating-current thin-film electroluminescent (ACTFEL) devices are presented. Since SPICE is commonly used by circuit engineers to simulate electronic circuits, the availability of accurate SPICE-based ACTFEL device models is useful in designing display driver electronics as well as for investigating ACTFEL device operation.

First, an ACTFEL model based on the built-in HSPICE Fowler-Nordheim tunneling diode is developed. The model, shown in Fig. 1, consists of a Fowler-Nordheim diode, which accounts for the tunnel-emission of electrons into the phosphor layer, in parallel with a capacitor and a resistor, which account for the phosphor capacitance and leakage charge, respectively. These are sandwiched in series between two capacitors which account for the ACTFEL insulator capacitance. The model is completely characterized by only two adjustable parameters: the emission barrier height and the phosphor shunt resistance. In contrast, five to seven adjustable parameters typically characterize back-to-back Zener diode ACTFEL SPICE models.

Second, a device physics-based ACTFEL model is developed for SPICE in which interface emission of electrons can occur via both pure tunneling or thermal emission and in which occupancy of the interfacial trap is considered. This model includes two sheets of charge at specified locations

within the phosphor layer which are used to model space charge creation through either field emission or trap-to-band impact ionization. The equivalent-circuit model of the device for forward bias is shown in Fig. 2, in which three emission currents and three space charge capture currents are represented by six voltage-controlled dependent current sources. Device-physics features, such as field- and occupancy-dependent trapping of electrons at each sheet of charge, are included in the SPICE model for the first time.

Detailed derivations of these models and further discussion of results are found in the references cited. [1, 2]

## Results and Discussion

The Fowler-Nordheim ACTFEL SPICE model reproduces with unprecedented accuracy the steady-state and transient electrical characteristics of evaporated ZnS:Mn devices. The excellent agreement between simulation and experimental data is illustrated by Fig. 3, which shows an external charge vs. applied voltage (Q-V) plot [3] of a 650 nm thick ZnS:Mn ACTFEL device driven 40 V over threshold by a 1 kHz bipolar trapezoidal waveform. The model correctly accounts for the steady-state field, turn-on voltage, and charge transfer within the ACTFEL device. However, as the upper curve in the maximum external charge vs. maximum voltage ( $Q_{\max}^e$ - $V_{\max}$ ) plot [4] shown in Fig. 4 indicates, the model parameters are optimized for operation at 40 V over threshold; the fit to measured data becomes increasingly poor near threshold. This situation can be remedied by varying the model parameters. When the interface trap depth and phosphor resistance are given suitable exponential dependencies on the overvoltage applied to the device, the lower curve in Fig. 4 results, showing good agreement with experimentally measured maximum transferred charge measurements.

The most obvious benefit of double-sheet charge model is the ability to simulate both symmetric and asymmetric capacitance overshoot, which occurs when dynamic space charge is created within

the phosphor concomitantly with the emission of electrons from the phosphor-insulator interface. Figure 5 shows a Q-V plot which exhibits effects of dynamic space charge creation via trap-to-band impact ionization. In addition to modeling dynamic space charge, the double-sheet charge model can also be used to simulate static space charge by controlling the rate at which space charge is destroyed. In this way, device behavior over a wide range of applied voltages is modeled better than for the Fowler-Nordheim diode. Figure 6 shows a  $Q_{\max}^e - V_{\max}$  plot showing output from the double-sheet charge model with static space charge (line) against experimentally measured data (dots). Note that the slope of the curve immediately after threshold is higher than the insulator capacitance. Thus, the double-sheet charge model is capable of simulating transferred charge capacitance overshoot; this important aspect of ZnS:Mn ACTFEL behavior has never before been simulated via SPICE. The model also correctly predicts the absence of transferred charge capacitance overshoot when the device is subjected to certain excitation schemes.

The accuracy of these SPICE models and their ability to simulate static space charge suggests that full electro-optic simulation of ACTFEL devices is now possible, with the inclusion of an optical SPICE model which accounts for the luminance response of the device. Optical SPICE models developed to date will be presented.

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## References

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- [2] J. P. Bender, M. S. Thesis, Oregon State University (2000).
- [3] Y. S. Chen and D. C. Krupka, *J. Appl. Phys.*, **43**, 4089-96 (1972).
- [4] R. Myers and J. F. Wager, *J. Appl. Phys.*, **81**, 506-510 (1997).

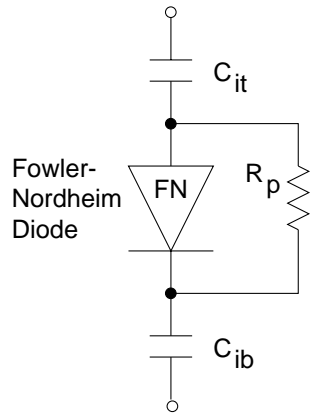


Figure 1: ACTFEL equivalent circuit using the SPICE Fowler-Nordheim diode model.

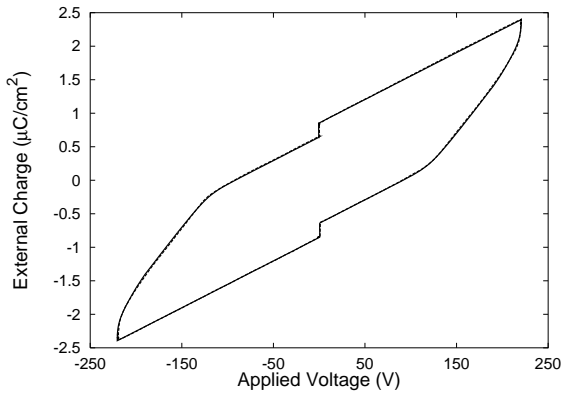


Figure 3: Q-V plot showing simulated (solid line) and measured (dashed line) data. The SPICE Fowler-Nordheim diode model is employed for the simulation.

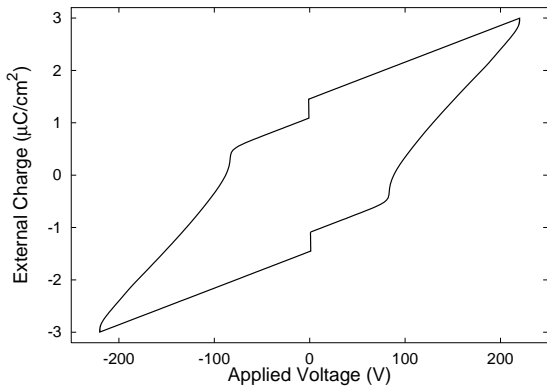


Figure 5: Q-V and Q-F<sub>p</sub> plots created using the double-sheet charge model with space charge creation via trap-to-band impact ionization.

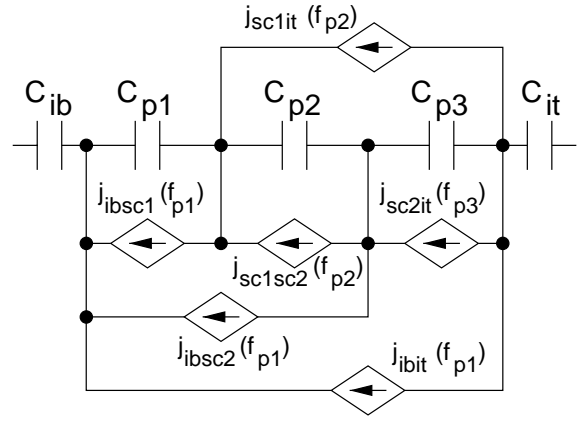


Figure 2: Equivalent circuit model for the two-sheet charge model under forward bias.

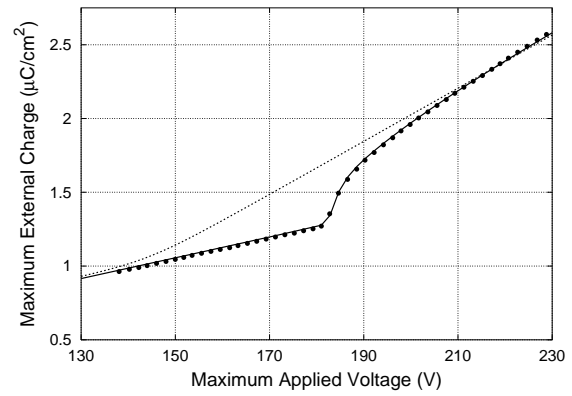


Figure 4:  $Q_{\max}^e$ - $V_{\max}$  plots showing measured data (dots) and data simulated using two variations of the Fowler-Nordheim model.

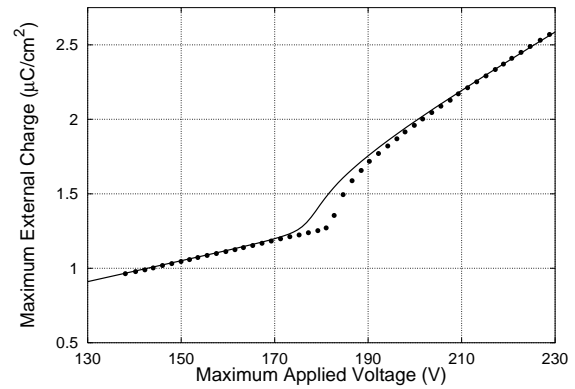


Figure 6:  $Q_{\max}^e$ - $V_{\max}$  plot showing measured data (dots) and output from the double-sheet charge model (solid line). Notice that the double-sheet charge model exhibits transferred charge capacitance overshoot.