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FROM ATOMS TO SYSTEMS

SPICE Modeling Solutions For Display Technologies

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December 2020

Outline

- Silvaco Modeling Solutions
- TFT Models in SmartSpice and Utmost IV
- TFT Frequency Dispersion Effect
- OLED SPICE Modeling
- Micro-LED SPICE Modeling
- Conclusions

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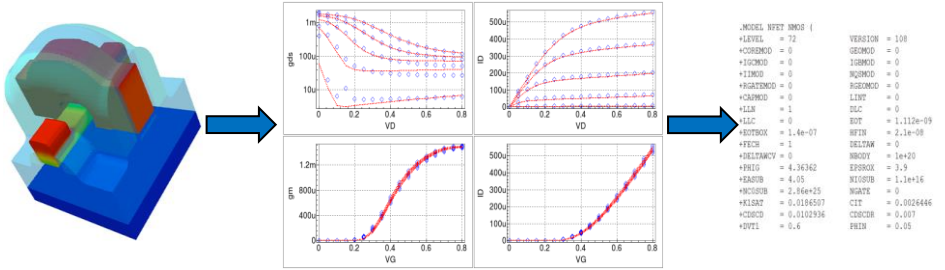
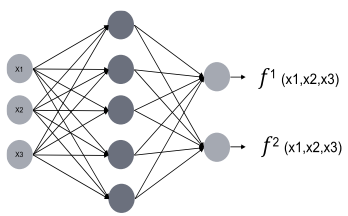
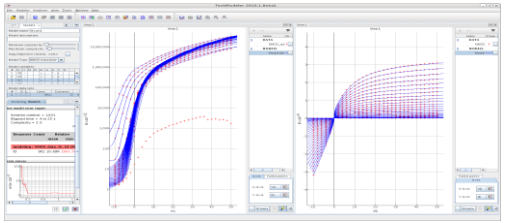
Introduction: SPICE Modeling Software and Services

- UTMOST IV
  - Extract and validate SPICE parametric models
  - Data from measurement equipment or TCAD
  - High-speed simulation
  - Verilog-A and macromodel support



- TechModeler
  - Advanced Machine Learning approach to modeling using approximation functions
  - Complement to UTMOST IV
  - Modeling solution for novel/special devices and phenomena (e.g., NBI Stress)





- Modeling Services

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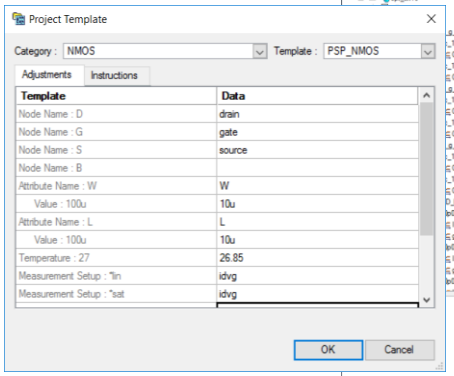
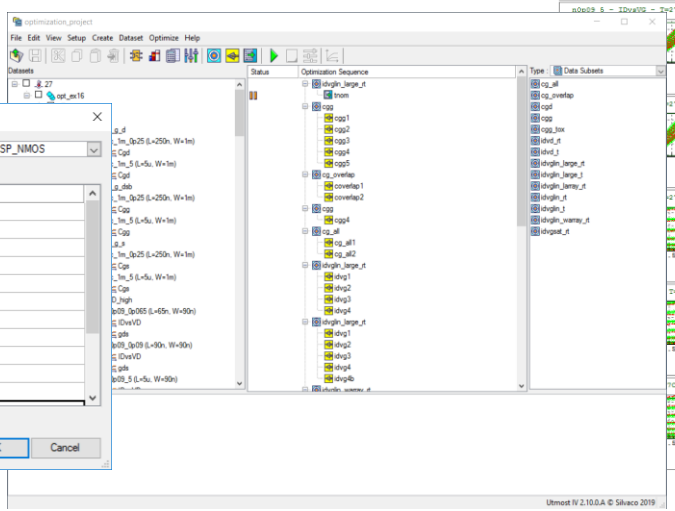
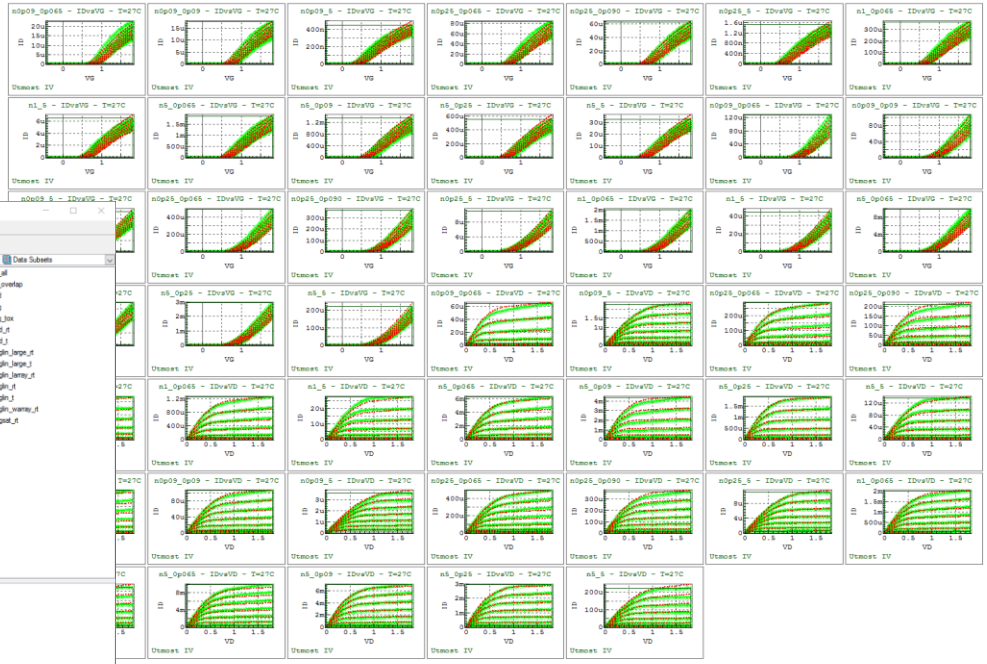
Quick-Start Optimization Templates

- Help users create optimization projects for their data
- Do not require modeling expertise
- Easy 4 step process
- Project configuration for the user's data
- Quickly achieve accurate model cards







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TFT Models In SmartSpice And UTMOST IV

- RPI amorphous Si TFT (Level 35), Versions 1 and 2
- RPI poly-Si TFT (Level 36), Versions 1 and 2
- Universal Organic TFT (UOTFT, Level 37)
- CINVESTAV-URV Metal-Oxide TFT (MOTFT, Level 38)
- Various custom models (Verilog-A, macromodels)

- Quick-Start optimization templates for RPI TFT models in UTMOST IV

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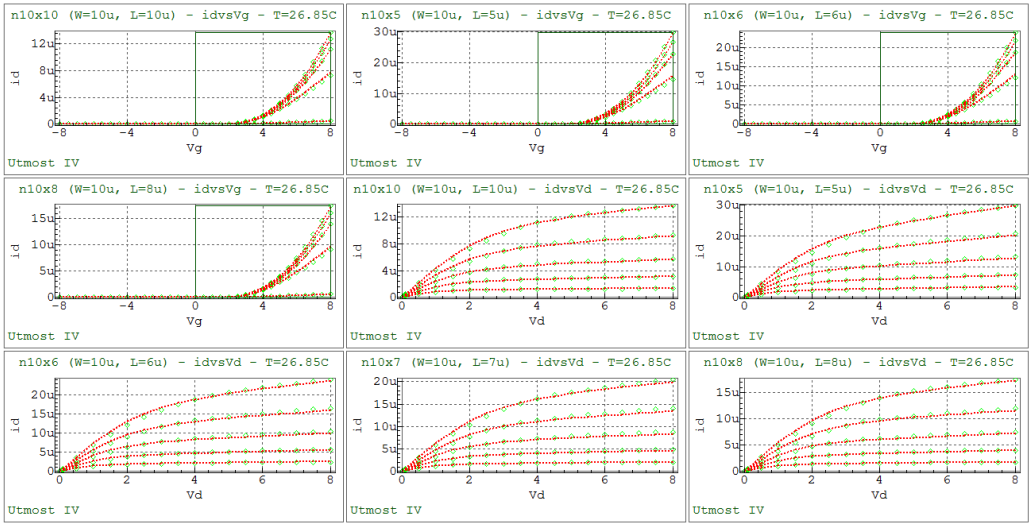
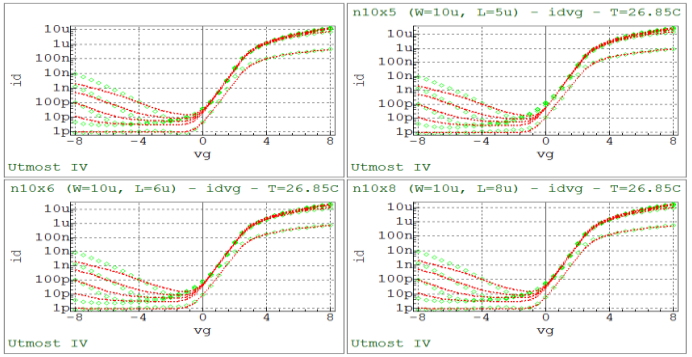
Poly-Si TFT Quick-Start Template Example

- TCAD-generated data
- 5 channel lengths
- Modeled in UTMOST IV using SmartSpice RPI Level 36 model.





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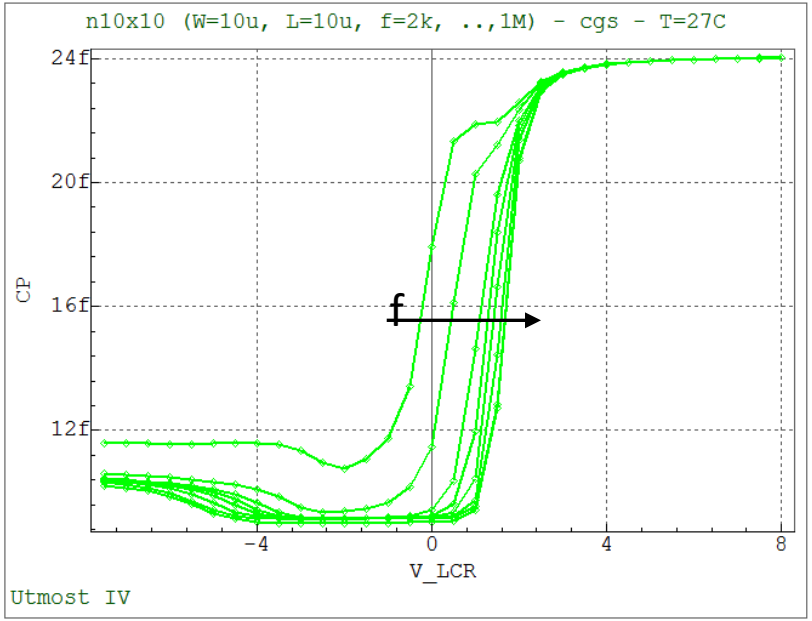
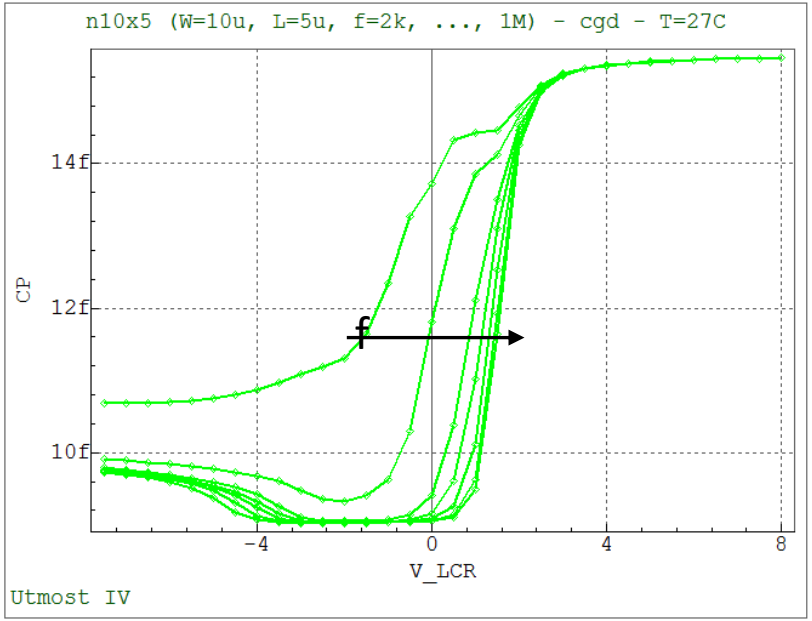
Frequency Dispersion

- Shift in C-V characteristics with frequency
- More pronounced for short channel and lower frequency



L=10um, f=2kHz, …, 1MHz



L=5um, f=2kHz, …, 1MHz

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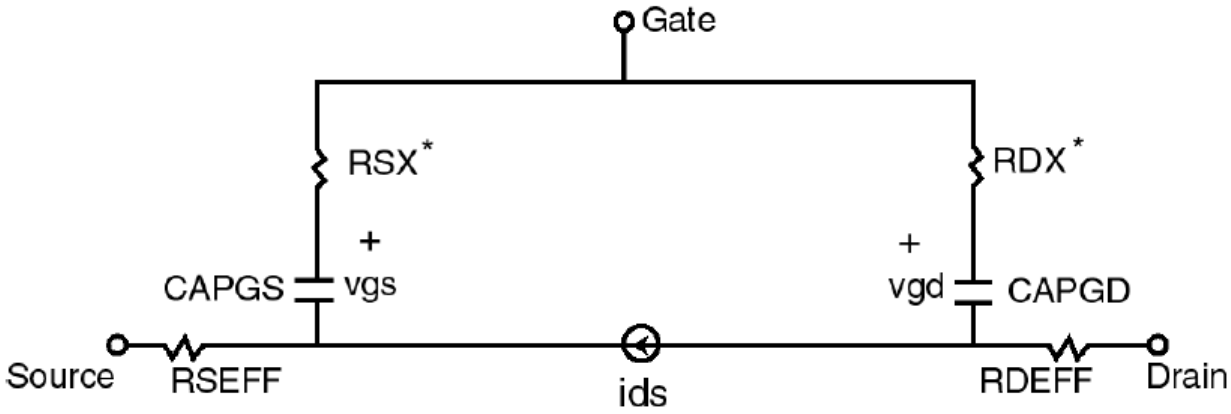
Frequency Dispersion Modeling: RPI TFT Models

- RSX and RDX elements in series with Cgs and Cgd, respectively



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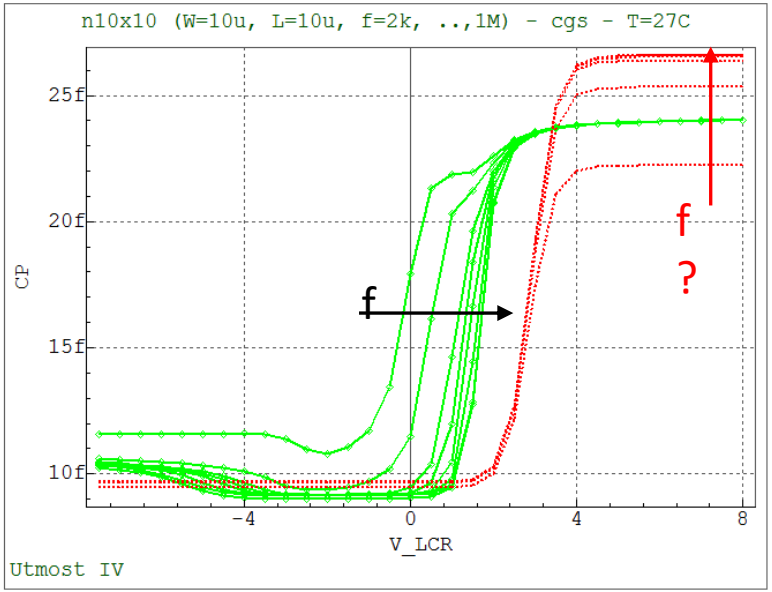
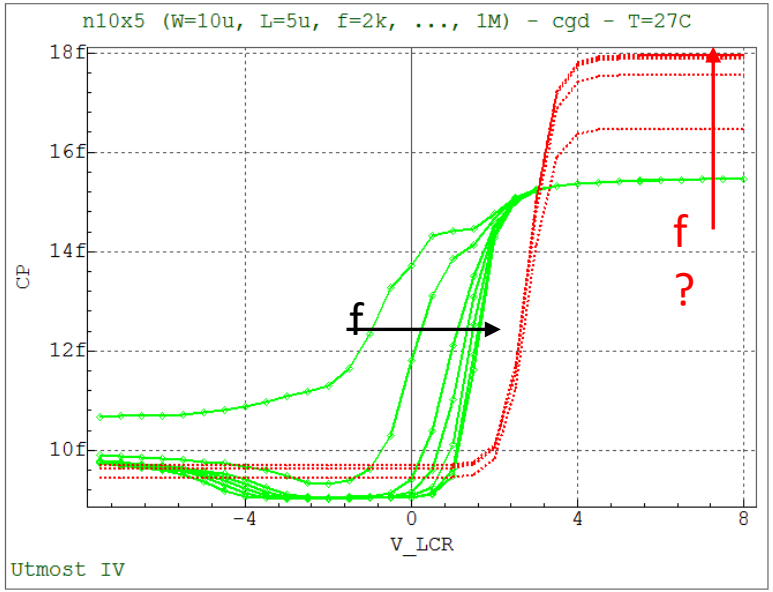
Frequency Dispersion Modeling: RPI TFT Models (cont.)

- Modeling the frequency dispersion through RSX and RDX is not adequate
- (Shifts the capacitance value instead)



L=10um, f=2kHz, …, 1MHz



L=5um, f=2kHz, …, 1MHz

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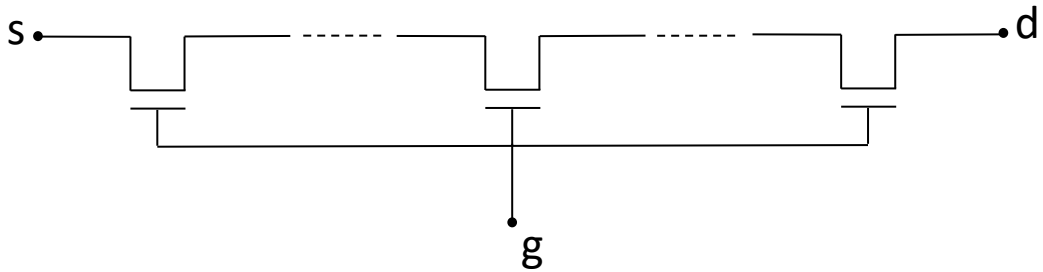
Frequency Dispersion Physical Modeling

- Due to the distributed nature of the channel
- Can be handled by effectively splitting the channel into multiple devices connected in series
- Model valid for AC as well as for transient analysis
- The number of devices: a trade-off between simulation accuracy and speed



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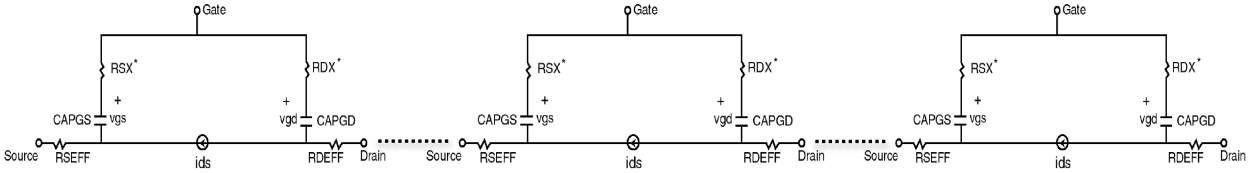
Frequency Dispersion Modeling with UTMOST and SmartSpice

- The overlap Cgs/Cgd and RSX/RDX are different between the edge and center devices.
- Handled by using the SmartSpice-specific AKO model feature:

```
R1 d d0 res
M1 d0 g d1 ntft_drain W='W' L='0.1*L'
M2 d1 g d2 ntft W='W' L='0.1*L’
…
M9 d8 g d9 ntft W='W' L='0.1*L'
M10 d9 g s0 ntft_source W='W' L='0.1*L'
R2 s0 s res

.MODEL ntft_source AKO:ntft ntft
+CGSO='cov2'
+RSX='rx’

.MODEL ntft_drain AKO:ntft ntft
+CGDO='cov2'
+RDX='rx'
```



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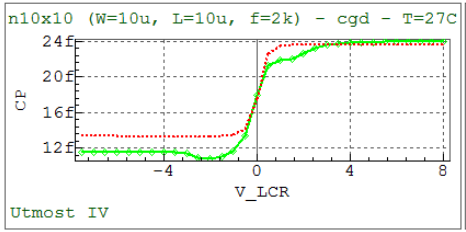
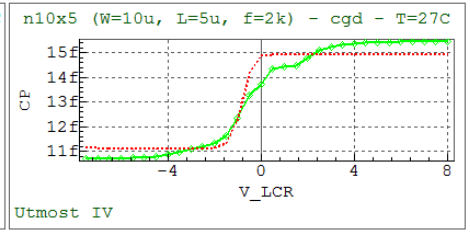
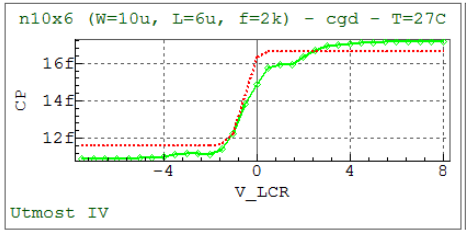
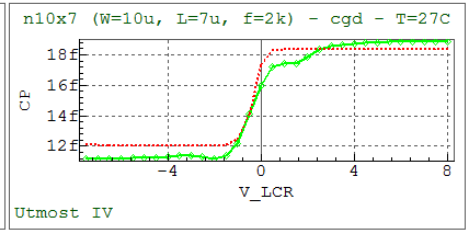
Frequency Dispersion Modeling Results: 3 Channel Segments

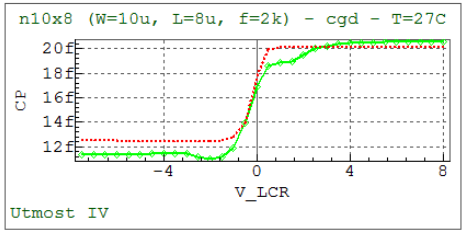
- Splitting the channel into 3 devices would be a good trade-off for this



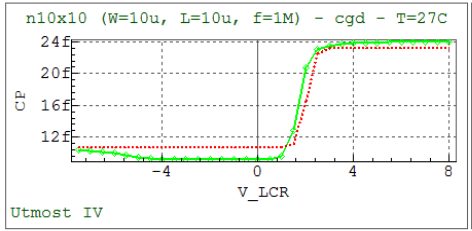


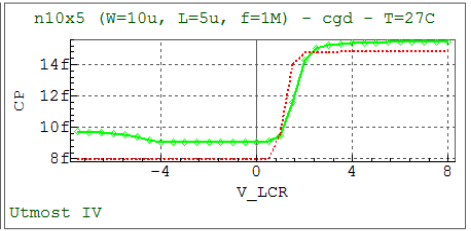


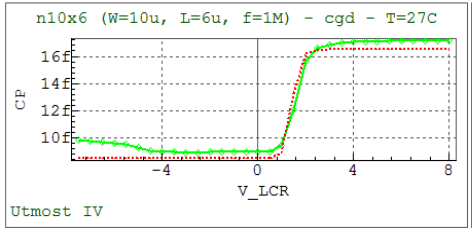


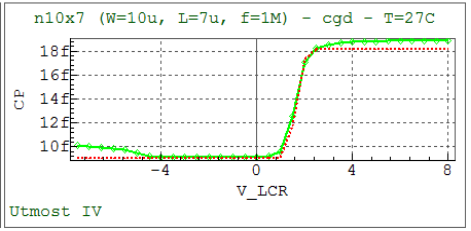


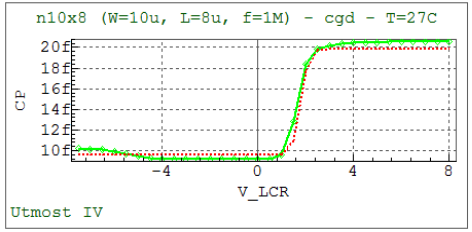
L=5um, …, 10um, f=2kHz











L=5um, …, 10um, f=1MHz

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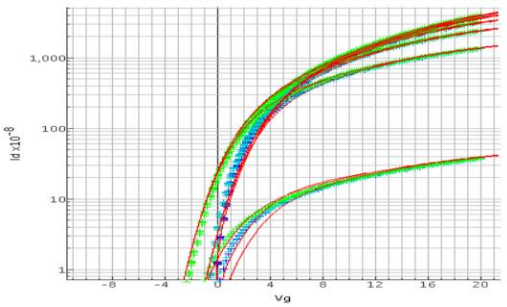
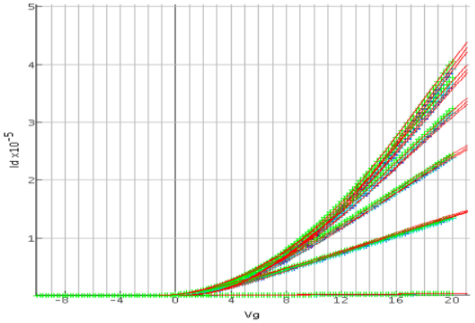
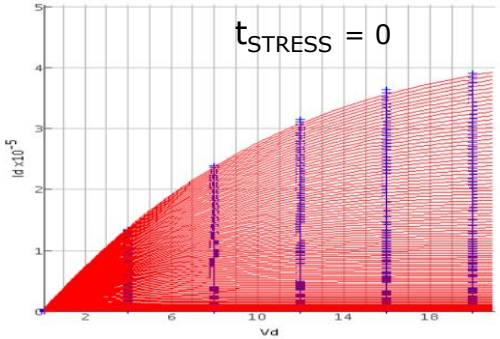
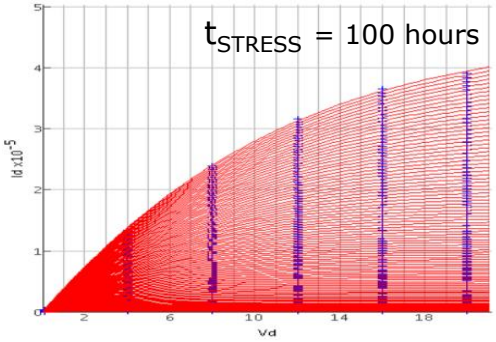
Modeling New Phenomena With TechModeler: NBIS for IGZO

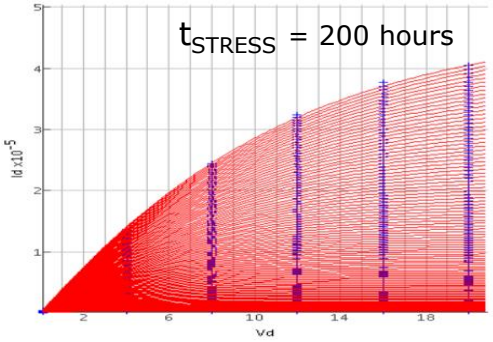
- Negative Bias Illumination Stress effect on IGZO modeled using TechModeler











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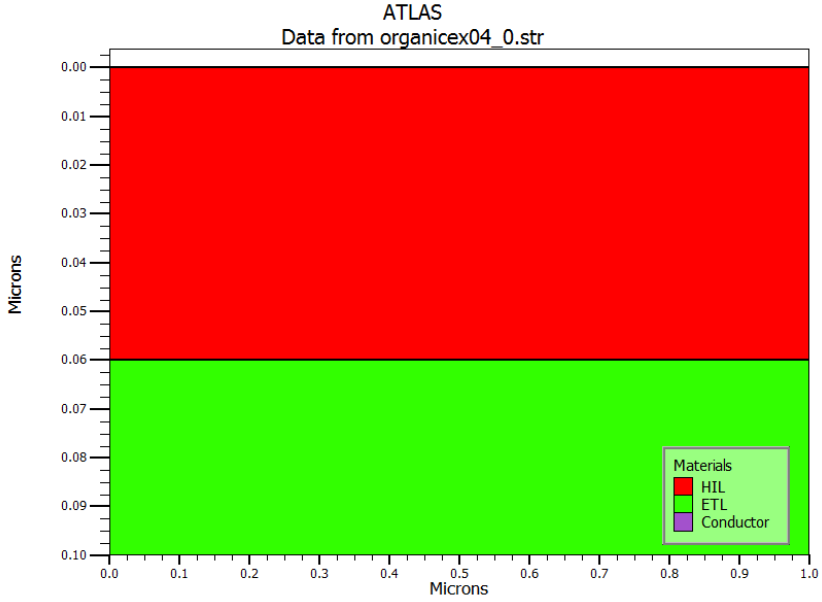
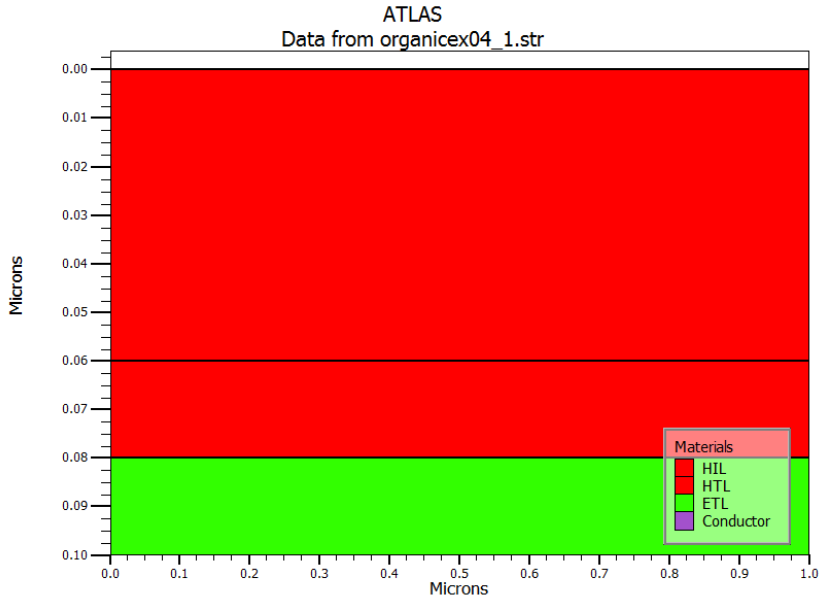
OLED Modeling

- Using TCAD-generated data to develop physical models
- Starting with two basic TCAD OLED structures, calibrated against published data



2-layer OLED



3-layer OLED

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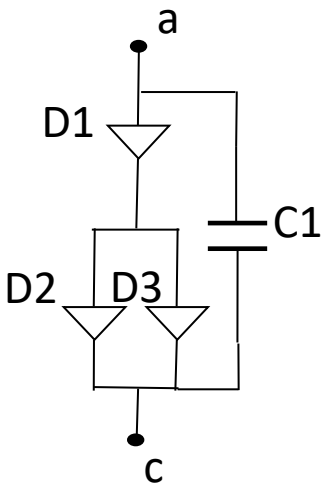
OLED SPICE Macromodel

- Developing a physics-based macromodel based on the 2-layer OLED structure
- The current transport is bulk-limited and injection-limited
- These phenomena can be modeled by a regular diode D1 in series with a Fowler-Nordheim (Level 2) tunneling diode*, D2
- An additional diode, D3, is needed to compensate for the capacitance of the Fowler-Nordheim diode element.
- Additional circuit elements are used for modeling the luminous power output



*J. P. Bender at al., “OLED Modeling via SPICE”, Oregon State University

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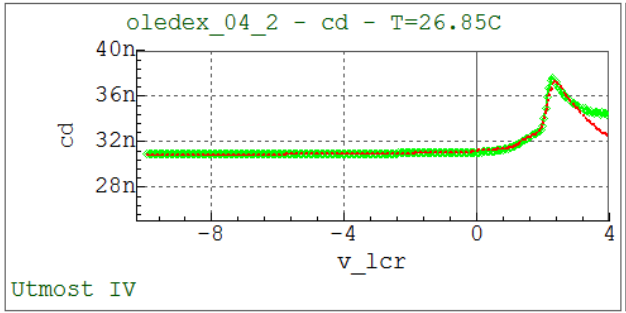
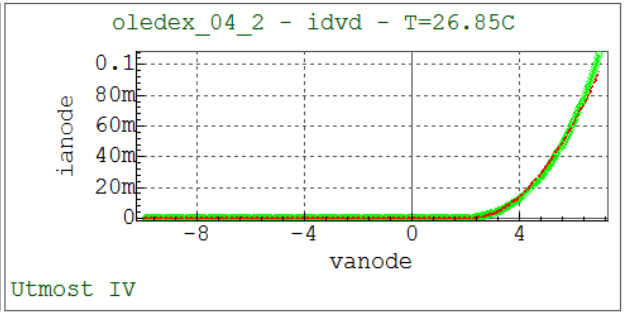
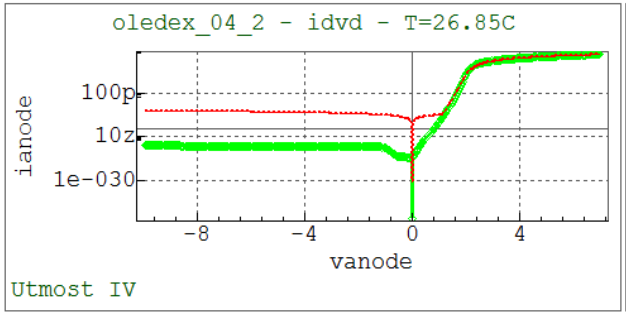
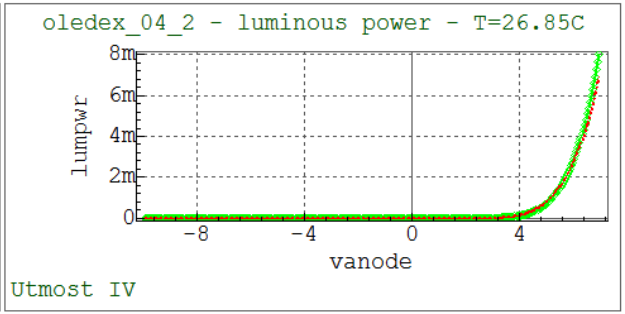
OLED Macromodel Results: 2-layer Structure

- The I-V, C-V and luminous power characteristics are accurately modeled
- If needed, the very low reverse current can be modeled using TCAD mixed-mode SPICE simulation, with extended precision









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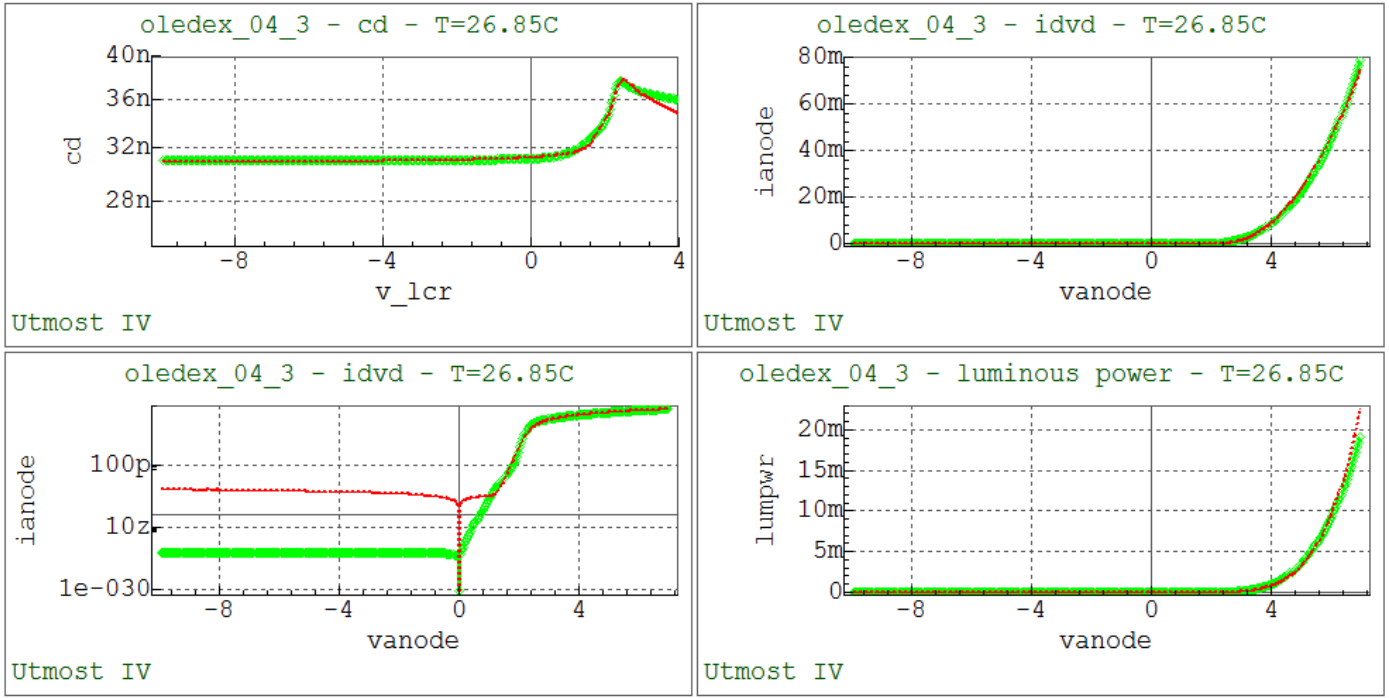
OLED Macromodel Results: 3-layer Structure

- The model developed based on the 2-layer OLED can also accurately describe the 3-layer device



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OLED Silvaco Model

- Implemented using Verilog-A
- Ongoing development
- The luminous power output can be also added, similarly to the previous example

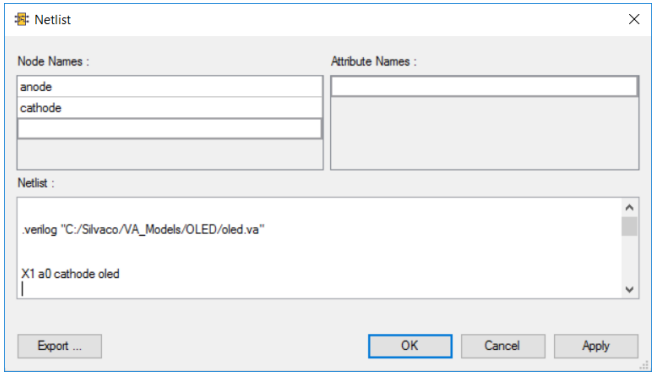
```
/* OLED model
 *
 * This implementation is
 * Copyright (C) 1984 - 2020
 * Silvaco Inc. All rights reserved
 *
*/

`include "discipline.h"
`include "constants.h"

`define EPSOX   3.453133e-11
`define N_MINLOG  1E-38
`define CHARGE 1.6021918e-19
`define K_Q (8.6170869180581252e-005)

module oled(a, c);
    inout a, c;
    electrical a, c;
    electrical asw, as;

    // instance parameters
    (* desc = "Instance operating temperature difference",  units = "degC" *)
    (* desc = "Instance operating temperature difference",  units = "degC" *)
    (* desc = "Instance operating temperature",  units = "degC" *)
```



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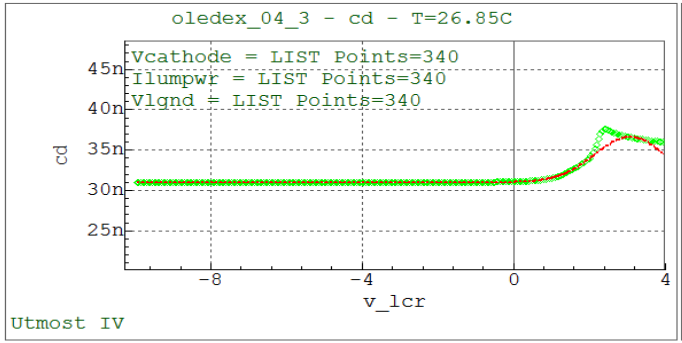
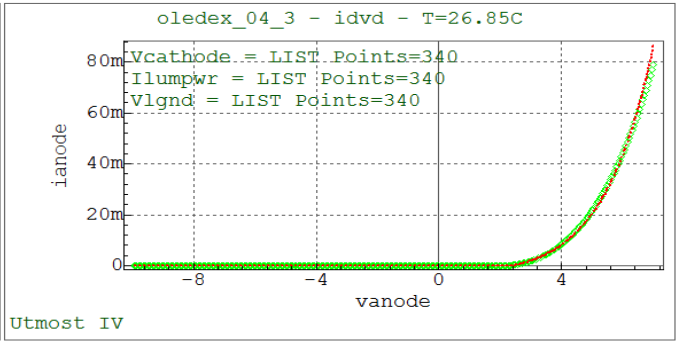
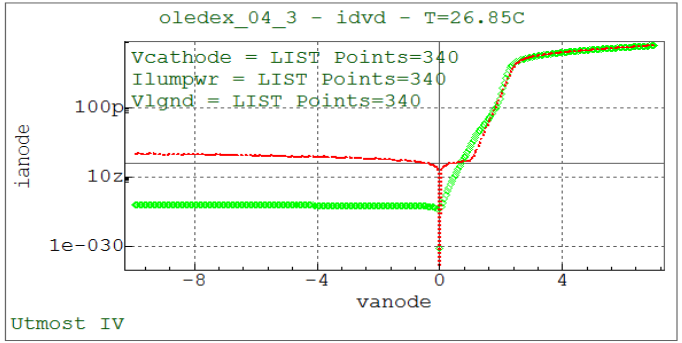
OLED Compact Model Results: 3-layer Structure

- 3-layer OLED structure characteristics using the Silvaco proprietary Verilog-A compact model







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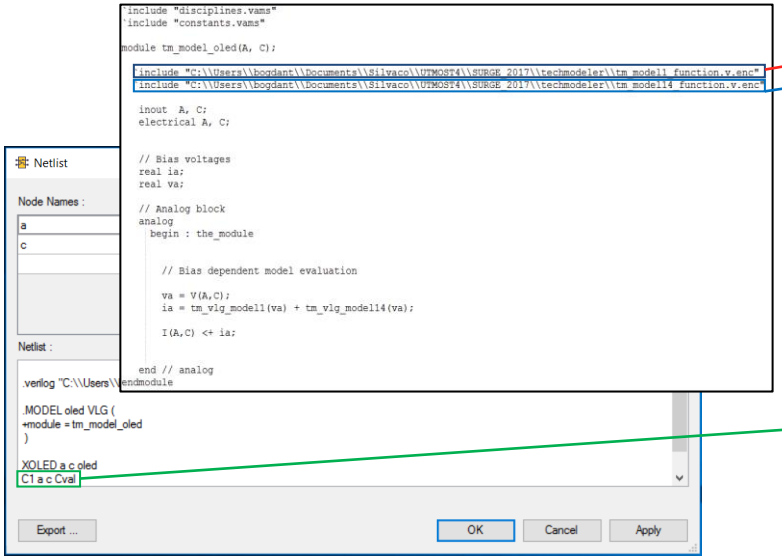
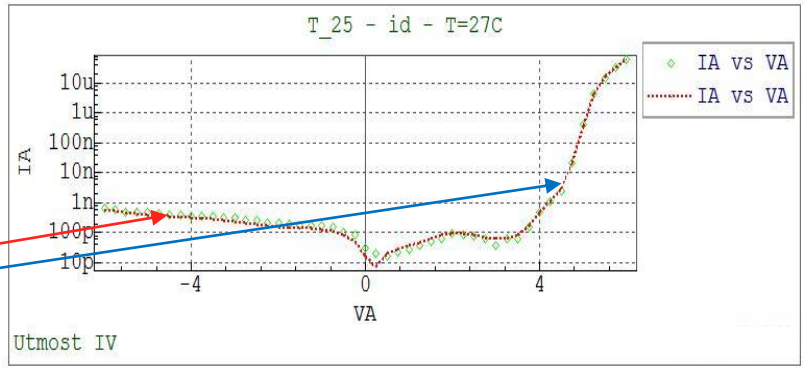
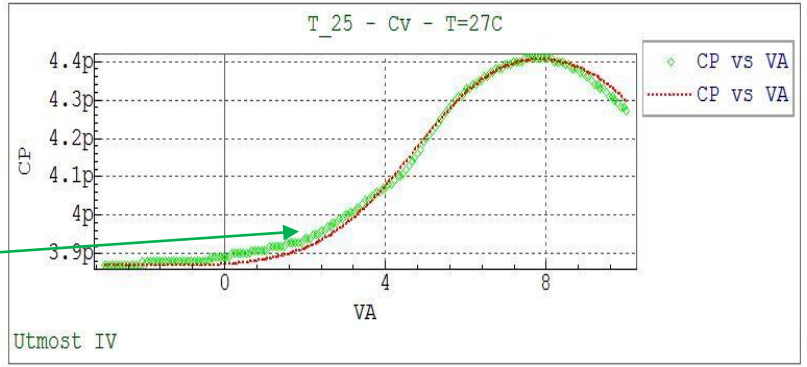
Alternative OLED Modeling using UTMOST IV Verilog-A and TechModeler

- OLED model
  - I-V model created with TechModeler
  - C-V macromodel extracted using Utmost
  - Models combined in Utmost using Verilog-A







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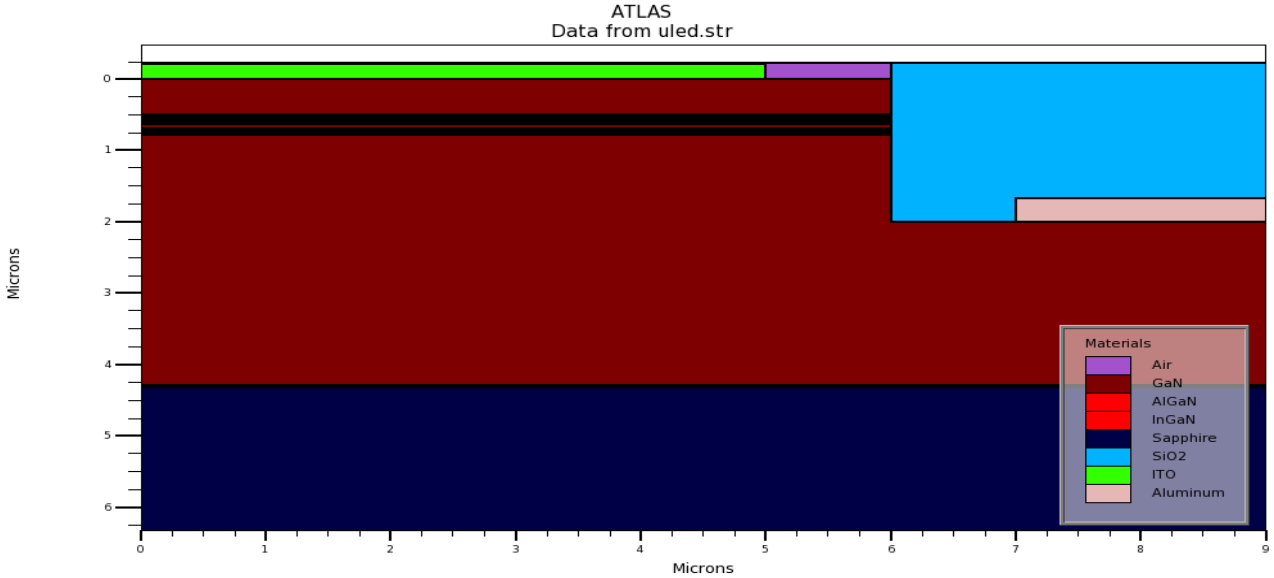
Micro-LED Modeling

- TCAD 12μm Micro-LED structure
- Calibrated against published data



*H. X. Jiang at al., “III-Nitride Blue Microdisplays ”, Applied Physics Letters 78, 1303 (2001)

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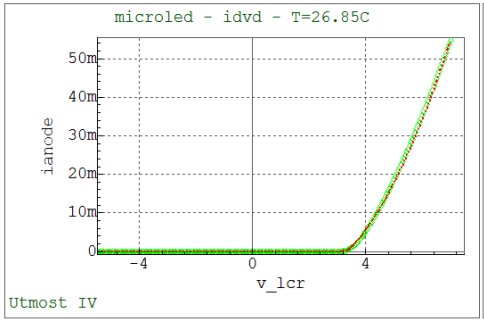
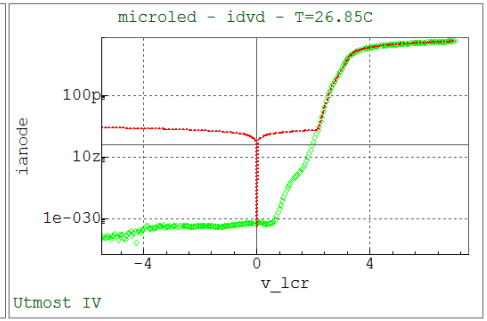
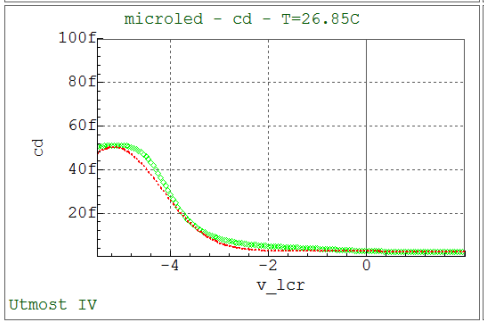
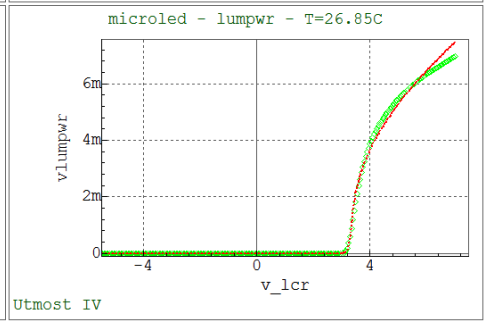
Micro-LED Compact Model Results

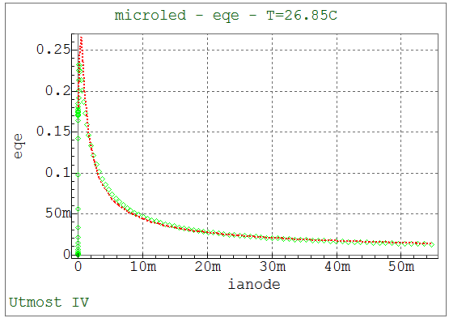
- Micro-LED structure characteristics using the Silvaco proprietary compact OLED model
- Added the luminous power output using a special macromodel
- Accurately describing the quantum efficiency dependence on device current.











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Conclusion

- Complete modeling solution: UTMOST IV, TechModeler and modeling services
- TFT modeling capabilities of UTMOST IV and SmartSpice
- Modeling the TFT frequency dispersion effect using channel splitting
- OLED modeling examples
- Micro-LED modeling example
- Using the combined capabilities of Silvaco TCAD, UTMOST IV and SmartSpice to accurately model TFT, OLED and micro-LED devices

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Thank you!

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