The Role of TCAD in Compact Modeling

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Applied Materials

Michael apologizes for not being able to be here today.

This talk will discuss how TCAD is used (and not used) in compact modeling. There *should* be a natural connection between the two groups, but he feels that there actually is a significant barrier -- or at least, there is not as much collaboration as there could be.

Goals

- The goals of this talk are to
  - explore the role of TCAD in compact modeling, and
  - encourage compact modelers to make better use of TCAD.

(just read this slide)

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Outline

- Review of TCAD
- TCAD at Applied Materials
- Rev0 models from TCAD
- Use of TCAD for compact model development
- Future opportunities

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Although this audience is probably familiar with what TCAD is, we will start with a brief discussion of what TCAD can and cannot do.

Then, to answer your question, “Yes, we do use TCAD at Applied Materials”, and there a few slides describing that activity.

Next, TCAD can be used for generating pre-silicon, or Rev0 models. There are probably some skeptics to this approach in the audience, so the benefits of simulation-based Rev0 models will be presented.

Finally, a brief discussion of how TCAD had not been used much for the *development* of compact models, and a few opportunities for collaboration between TCAD and compact modeling.

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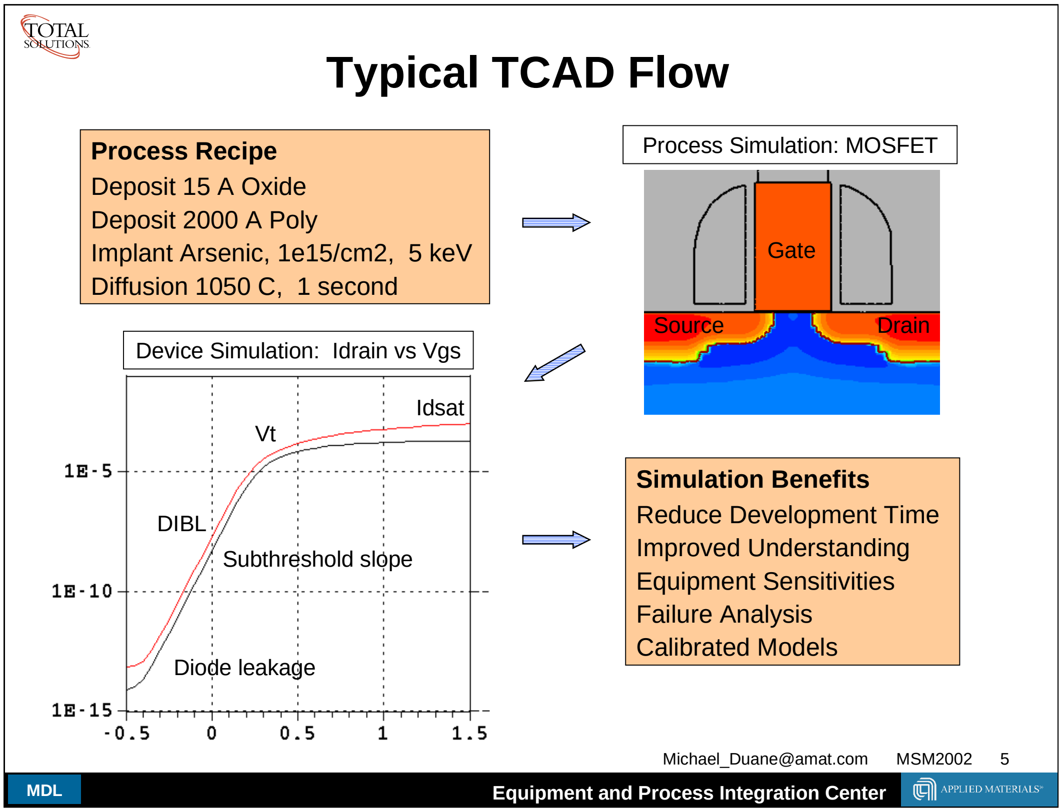
Common TCAD Programs

- TCAD is process and device simulation. Widely used at IC manufacturers during technology development; 20+ year history.
- Software examples:
  - SUPREM, PISCES, PROPHET
  - Athena and Atlas
  - TSUPREM4, MEDICI, TAURUS
  - DIOS and DESSIS
  - and many others.

The point of this slide is that TCAD is fairly established. In a few minutes, we will talk about the problems with TCAD. There have been dozens of TCAD programs over the years. The list above focuses on the commercially available ones. As I write the notes for this slide, I suddenly wonder whether all these programs diluted the TCAD effort too much over time.



This slide shows the typical flow in TCAD simulation. Starting from a process recipe and knowledge of the layout, a structure is created via process simulation. This structure feeds directly into the device simulator, which produces IV or CV curves.

There are many benefits from simulation, and one of the more important ones is a better understanding of how devices really operate. As an example, you can plot where the current flows in the “off” condition - whether it is surface or sub-surface conduction. Many textbooks talk about current flow deep in the substrate, but I haven’t seen that in many years. Poly depletion is another interesting example. You can see how the depletion layer thickness varies across the channel.

I have used TCAD many time for failure analysis, or detective work. If a lot has unexpected behavior, can that behavior be re-created in simulation with some assumptions about how it was misprocessed?

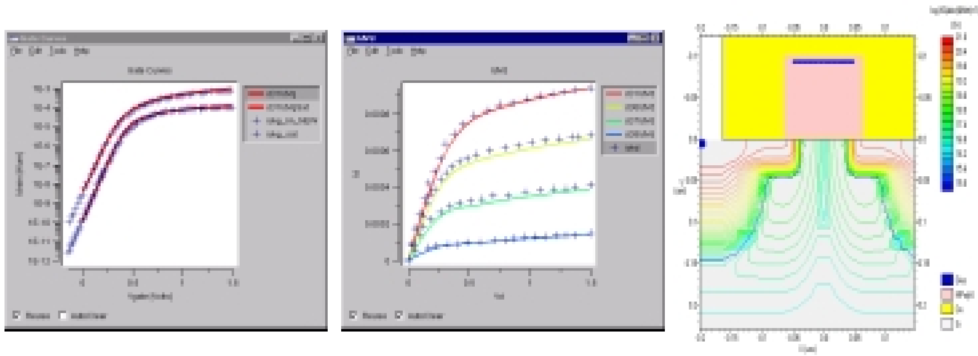
Device Synthesis

- Device simulation can also be performed without process simulation.
  - doping profiles specified as Gaussian functions.
  - this approach is particularly relevant in the context of compact model generation.

Although the previous slide showed process simulation as being the input to device simulation, most device simulators can create structures on their own. The doping profiles might not be as complicated as what a process simulator would predict, but it is good enough for many applications. And, this approach is very fast compared to process simulation. I first saw it used by a group simulating large power devices. At that time, the process simulation for those structures was 20 hours. Also good for people who don’t trust process simulators.

Inverse Modeling

- Inverse modeling of the Intel 1998 IEDM device via optimization of a parameterized device description.
  - Find structure to match electrical results



Figures courtesy of Sequoia Design Systems

Another TCAD application relevant to this discussion is the concept of inverse modeling. Here we start with known device characteristics, and then search for a structure that reproduces these curves. This is a situation where you want to use device simulation only. People worry about uniqueness, but you can add constraints to prevent unrealistic structures as solutions.

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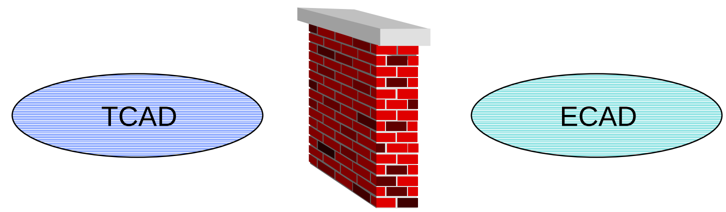
The TCAD-ECAD Connection

- Conceptually, TCAD results can be fed directly into ECAD.
- In reality, the TCAD and ECAD communities are rather distinct.
  - (although OPC and RC extraction has “successfully” moved to ECAD / EDA)



The original title of this talk was “TCAD and ECAD - is there a connection?”

It is not obvious why the connections are not better between the TCAD and ECAD worlds.

Next, we will explore some of the problems with TCAD, but the intent is to leave you with the impression that TCAD ***can*** be used for compact model generation.

Problems with TCAD

- There are still many TCAD skeptics
  - examples can always be found where the results don't match measurements
- Common sources of these differences
  - insufficient physics (new materials)
  - inaccuracies in metrology (especially L and tox)
  - improper use of software tools (gridding, models)
  - missing process details (temperature ramps)
  - hidden assumptions in the software
  - lack of 3D effects (narrow width, line edge roughness)
- But properly used, simulation can be a powerful tool

There are many reasons why TCAD simulations don't match silicon measurements, but this isn't always because of inadequacies in the model. Often, there are too many models to select from, and the proper selection will give the desired results.

If technology would just stop evolving for a while, I am sure that TCAD could become highly predictive. :)

But the lack of a 3D process simulator is a serious problem. 3D device simulators have been around for many years.

And even though I have often spoken about the limitations of TCAD, I have done so so that others can be aware of the pitfalls, and avoid them.

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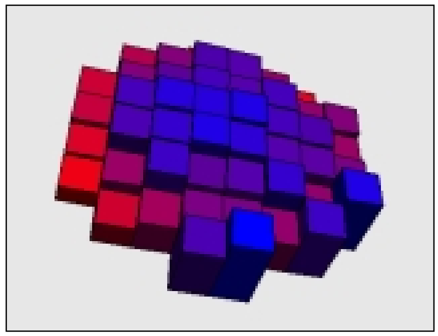
Process Variation

- Inherent process variations result in distributions of output variables.
  - Implications for calibration: adjacent die can have significantly different results.



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When calibrating TCAD, you have to know your structure *exactly,* or else simulate a range of input variables and see if your measured results fall with the simulated output range.

The figure here is real data, but it is an arbitrary example. It show a wafer map of some electrical parameter.

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Deterministic Modeling

- TCAD useful for estimating variation of output parameters based on assumed variation of input parameters (e.g., Vt as a function of L).
- One area where simulation outshines silicon experimentation is in the ability to control the process variation.
  - Corner models can be built where the gate length and tox variation are known exactly.
- TCAD enables correlations between compact model parameters and fab equipment settings.
  - *How do you adust a compact model coefficient in the fab?*

Along these same lines, simulation is good for generating realistic corner models. You can see how different Lgate control affects your circuit performance.

And you can gain insight into how process knobs affect compact models. A single knob might affect many compact models. But if your only source of compact models is fits to electrical data, how do you know how to “correct” a compact model coefficient?

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Further Reading

- Articles which explore TCAD calibration and limitations:
- *Limitations / Weaknesses of TCAD*, presented at 1993 Stanford review, available at http://www.fourfriends.com/tcad/limit.html
- *TCAD Needs and Applications from a User's Perspective*, IEICE special issue on TCAD; http://search.ieice.org/1999/pdf/e82-c_6_976.pdf
- *Challenges in Predictive Process Simulation*, http://www.ihp-ffo.de/chipps/97/Ddoc/dpgLong.html
- *TCAD Calibration: Challenges and Opportunities*, http://www.ihp-ffo.de/chipps/97/Djpg/Duane.html

For those of you interested in knowing more about TCAD calibration, please see the following online articles.

Same comment as before - although these articles expose TCAD weaknesses, the intent to improve the success rate of TCAD.

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TCAD at Applied Materials

- Applied has a major push in Process Module development, and TCAD is used to support this. Process Modules described in annual report:
  - http://www.appliedmaterials.com/financial/annual2001/AMAR01_FINAL.pdf
- Applied and ISE collaboration on process model calibration.
  - http://www.appliedmaterials.com/newsroom/pr-00261.html (Jan 2000)

Next, we will move on to a discussion of TCAD at Applied Materials. First, Applied is getting into the Process Module business, and TCAD is helpful for developing technology.

We also have a calibration project on-going with ISE (Integrated Systems Engineering), a TCAD vendor, to improve their tools, and to provide calibrated TCAD to our equipment customers.

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Dr. Dan Maydan
Process Module Technology Center

- Opened March 2002.
- 39,000 sq. feet of Class 1 cleanroom, with capacity for over 300 process and support tools.
- 248nm and 193nm litho capability for 300mm.
- The equipment industry's most advanced facility for process technology development.

We recently opened a new technology development center in Sunnyvale.

Recall that we are an equipment maker, so these are state of the art tools, and beyond even. Applied does not make litho equipment, so we rely on our litho partners. But again, state of the art tools.

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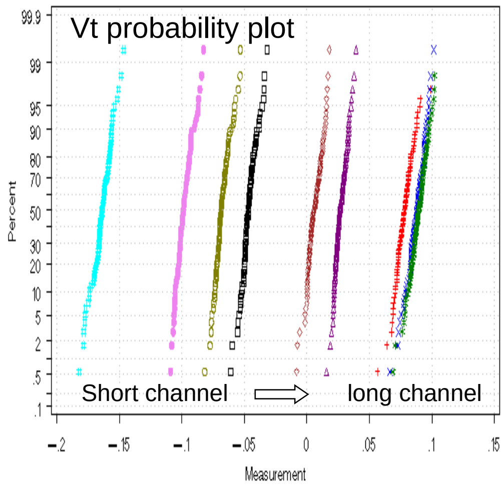
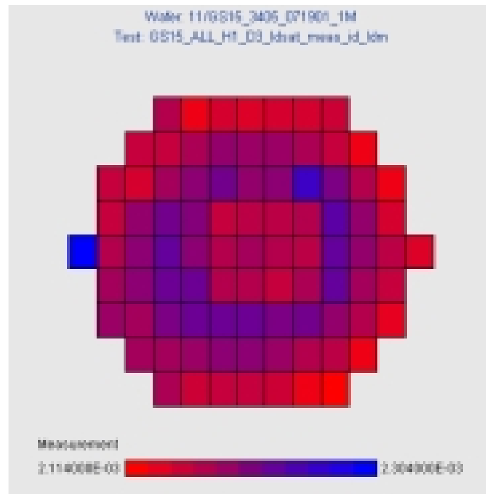
First 300mm Transistors at Applied Materials





Long channel Vt range only 35 mV on a 300 mm wafer!

Idsat wafer map for checking pattern dependencies.

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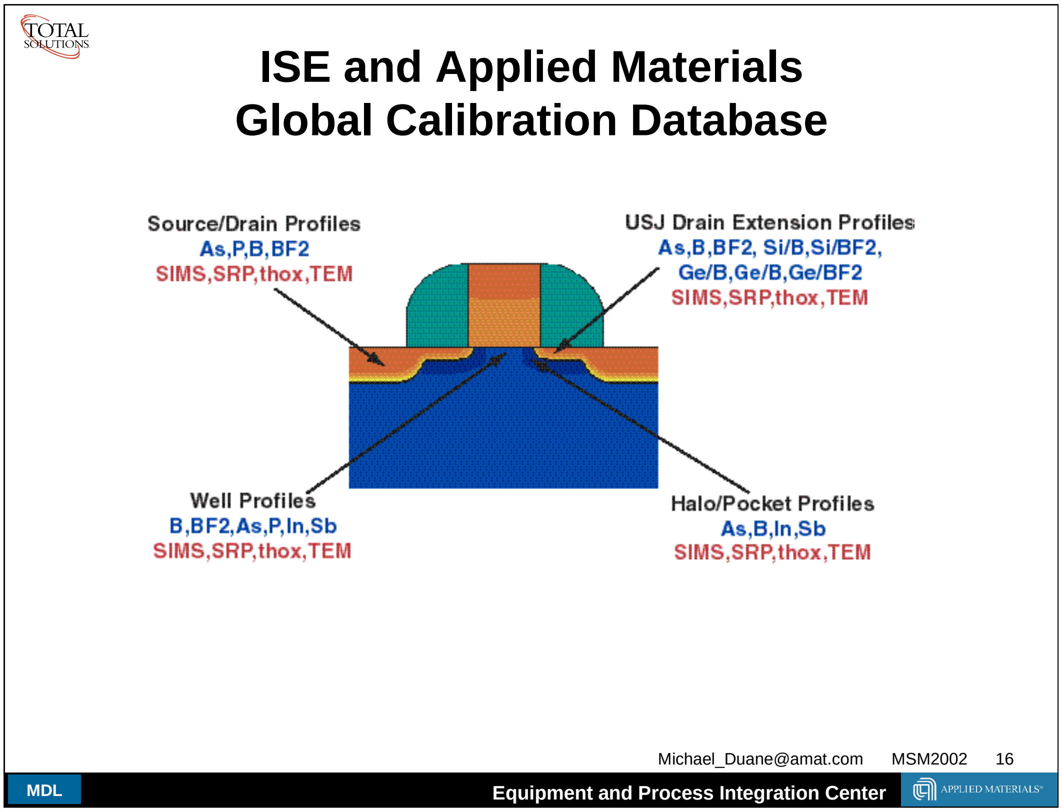
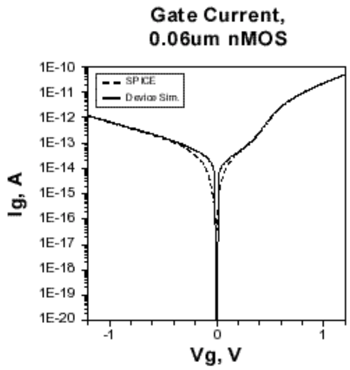
Last summer, we made our first 300mm transistors. This was a very simple flow. Still, for an equipment company, it was a major milestone.

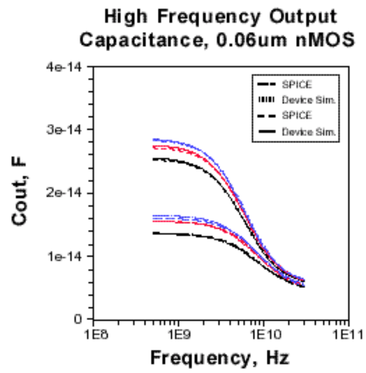
The figure on the left shows probability plots of Vt for different L on a single wafer, and the figure on the right shows a wafer map of Idsat.



The figure above shows some of the areas where the calibration project with ISE initially focused on. There has also been work on oxidation modeling. Literally hundreds of SIMS have been taken. This work is ongoing.

BSIM4 vs Device Simulations





Figures courtesy of ISE

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And these figures show how device simulators can reproduce deep submicron physics. A cynic might point out that I am just showing how a compact model can fit a device simulation, but there are equally good fits between silicon and TCAD not shown here.

TCAD for Compact Model Generation

- TCAD is routinely used for pre-silicon, or Rev0, compact models.
- In a pre-silicon scenario, the final process flow is not known. This only adds to the modeling uncertainty.
- However, a key advantage of TCAD based compact models is *self-consistency* - coefficients will show the proper trends and correlations.
  - improbable combinations of coefficients eliminated.
  - TCAD better at trends than absolute values.
  - Better understanding of how equipment setting affect compact model parameters.

Through personal knowledge, I know that Rev0 models are often created from TCAD. I did this for a 1M DRAM. However, there are few, if any, publications that demonstrate this.

I think an under-appreciated advantage of a simulation based compact model (as compared to an extrapolation of an existing model) is that the parameters will be more self-consistent.

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TCAD for Compact Model Generation (2)

- Other arguments in favor of a simulation based approach for compact model generation:
  - early in the design process, accuracy is less important than timeliness
  - the target Ion and Ioff are known, so that the TCAD results can be adjusted to meet these.
- Although compact models are usually a fit of the silicon data, an alternative approach is to use compact models as targets for the process to achieve !

(just read this slide, please)

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TCAD for Compact Model Generation (3)

- In a 1995 Compact Modeling Council meeting at SEMATECH, an informal survey of the use of TCAD for compact model generation showed:
  - Company A: hybrid approach for compact model generation using TCAD and experimental extrapolation.
  - Company B: Produced 0.35um models completely from TCAD based on a previously calibrated technology.
  - Company C: Has used TCAD in the past. But TCAD running into limitations. Expensive to “close the loop”.
  - Company D: Every generation has a new processing step and the modeling lags. So, TCAD doesn’t play a major role in technology development.

(the first three companies had significant internal TCAD groups)

In 1995, a Compact Modeling Council survey showed that the use of TCAD in generating compact models ranged from complete to none. The same results would probably be found today.

So the question for this audience of compact modelers is: how can TCAD play a larger role? Email me the answer, or tell the ITRS the next time around.

New Compact Models

- Conceptually, TCAD could be used to develop new compact models, not just the coefficients.
  - The BSIM model family has not used TCAD at all for this purpose.
  - A surprising gap in retrospect (from a TCAD perspective).
- But this is changing: “Generation of equivalent circuits from physics-based device simulation”
  - Pacelli, Mastrapasqua, and Luryi, IEEE Trans on CAD of IC’s, Nov 2000.

As far as I can tell, TCAD has historically not been used in the development of compact models. And considering how close Berkeley and Stanford are, I find this somewhat ironic.

But this is changing, as demonstrated in other talks in this workshop.

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Opportunities for TCAD / CM Development

- Looking forward:
  - how to couple advanced simulations (e.g. quantum scale) to compact modeling research.
  - Compact models in the ballistic limit
  - RF devices - interconnect modeling as important as silicon
    - transition frequencies, distortion, noise figures, etc.
  - New structures (double gate, FD SOI).
  - ESD modeling needs mixed-mode (device and circuit)
    - compact models can't handle breakdown

Here, I list some opportunities for collaboration between TCAD and compact modeling. We need to discuss how to best create the necessary interactions. But we are certainly approaching a regime where the device physics and even the device structure will be changing significantly.

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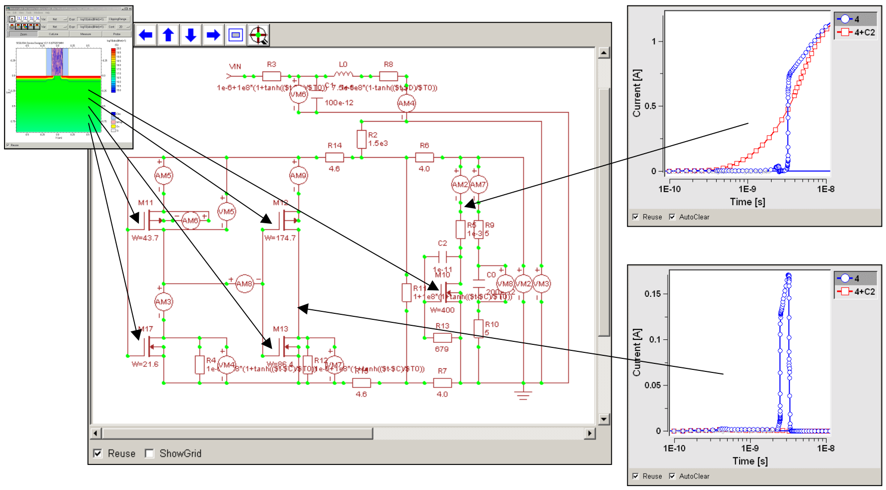
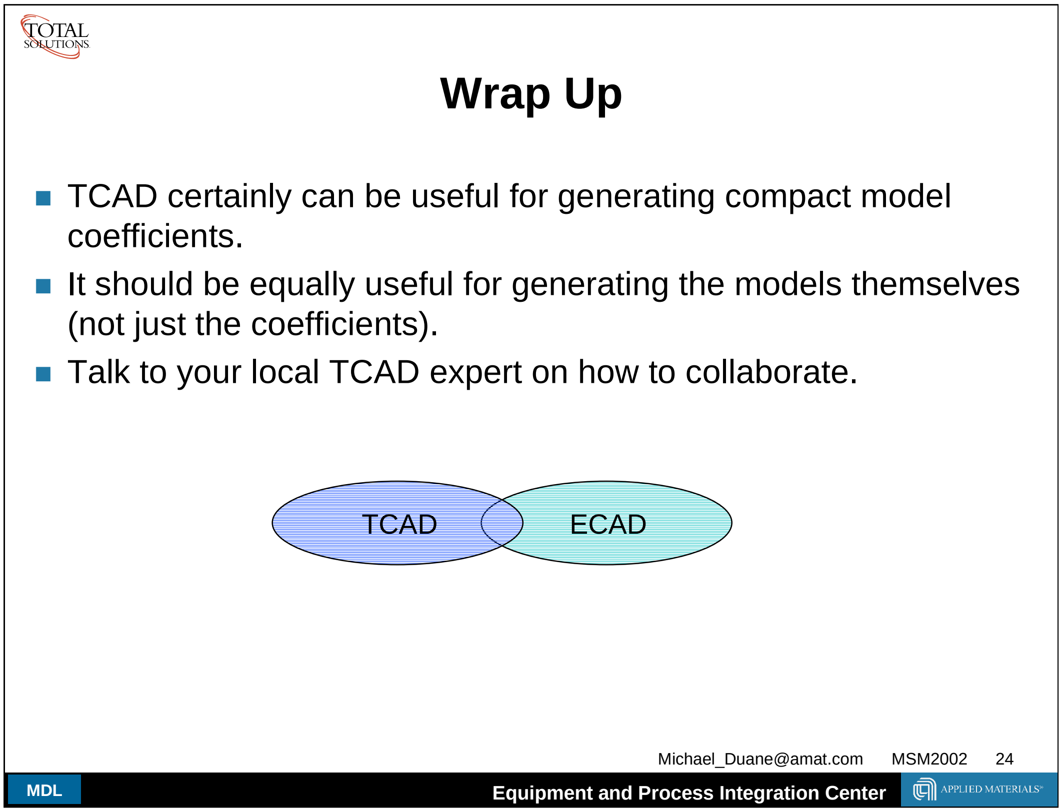
Mixed-mode Analysis of Complex ESD Events



Figures courtesy of Sequoia Design Systems

ESD is a special case worth highlighting. Here, I show a mixed-mode simulation where an actual transistor is simulated in a device simulator while part of a conventional circuit simulation. This is necessary in cases where there is no compact model that describes the electrical behavior of the device in certain operating conditions.



In conclusion, I hoped I have shown how TCAD can be useful for generating compact model coefficients, and I also hope TCAD will prove more useful in the future for creating compact models themselves. The way to achieve this remains open for discussion.

And finally, a special thanks to Zhou Xing for organizing this workshop and making my presentation.