Event-Driven Electrothermal Modeling of Mixed-Signal Circuits

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Introduction

- Project Goals
- Review of Electrothermal Modeling Techniques
- Fundamentals of Electrothermal Network Simulation
- Implementation of Event-Driven Modeling
- Simulation Results
- Conclusion

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Project Goals

- A primary goal of the semiconductor industry is to integrate more circuits onto a smaller chip.
- Thermal interactions will increase as the feature sizes decrease.
- Improperly managed heat may cause a failure of the designed chip.
- Existing methods for electrothermal simulation are time consuming.
- Focus of this work: to improve simulation efficiency by applying analog event-driven modeling techniques.

Review of Electrothermal Modeling Techniques

- Finite-element Analysis at the Device Level
  - Used to study individual device heating.
  - Highly accurate, but too computationally expensive.
- Lumped-element, Continuous-time Approximations at Circuit Level
  - Focused on modeling the physical effects of heat.
  - Effectively captures the heat diffusion.
  - Temperature is treated as a time-varying quantity.
  - Disadvantage: Simulation time increases unacceptably as the number of thermal interactions modeled increases.
- Mixed frequency/time domain reduction method
  - Specially optimized for reducing the order of thermal network.
  - Useful for performing full-chip transient electrothermal simulation.

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Fundamentals of Electrothermal Network Simulation

- **A typical electrothermal simulator contains three elements:**
  - **Electrothermal device models**, which provide temperature-dependent device characteristics.
  - **Thermal device models**, which compute the device temperature based on the power consumption data.
  - **Electrical device models**, which calculate terminal voltages.

- **In the proposed event-driven electrothermal simulation approach :**
  - All electrical models remain analog.
  - Electrothermal models are both analog and event-driven.
  - All thermal models are event-driven.

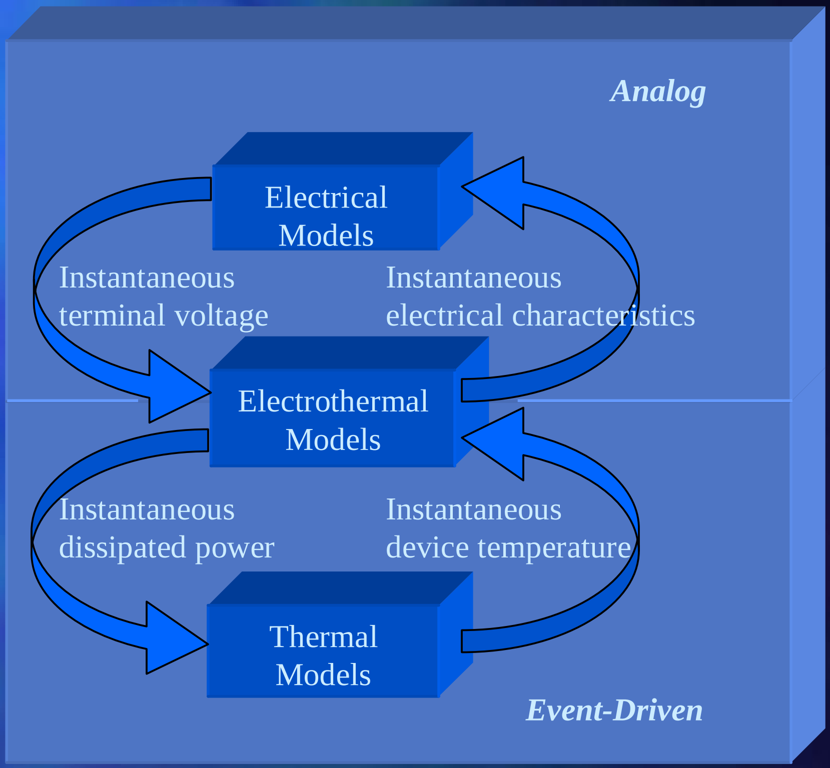

Fig. 1. Block diagram of a proposed event-driven electrothermal simulation approach.

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Fundamentals of Electrothermal Network Simulation , Cont. — Electrothermal Network

- Dynamic Thermal Analysis
  - The power dissipated is directly fed into the thermal network.
  - The temperature at the thermal node of a device is the operating temperature of the device.
  - The device model adjusts its behavior as a function of its operating temperature.
- Electrothermal Semiconductor Device Models
  - Interact with the thermal and electrical networks through the electrical and thermal terminals, respectively.
  - Use the instantaneous device temperature to evaluate the temperature-dependent properties.
  - Calculated power dissipation supplies heat to the surface of thermal models.

Fundamentals of Electrothermal Network Simulation , Cont. — Thermal Network

- Conservative System
  - Sum of all power contributions at a thermal node equals zero.
  - Temperature at all terminals connected to a thermal node is identical.
  - Through variables and across variables.
  - Power is the through variable and temperature is the across variable.
- Thermal Network
  - Solves for the dynamic temperature distribution.
  - Interconnection of thermal component models.

Implementation

- $\Gamma_{TH} >> \Gamma_{EN}$
  - Γ_{TH} :Time constants of thermal network.
  - Γ_{EN} :Time constants of electrical network.
  - Temperature can be evaluated less frequently.
- Mixed Signal Simulation.
  - Analog models are still used for electrical devices.
  - Thermal signals of the electrothermal model are approximated by analog event-driven signals.
  - Thermal models are entirely event-driven.

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Implementation, Cont.
—Electrothermal Semiconductor Models

- The electrothermal models couple electrical and thermal networks.
- Analog electrothermal models are required to model the power dissipation in devices and "sourcing" this power out of a thermal node.
- Analog event-driven modeling method
  - "Sourcing" of the power is performed at discrete intervals.
  - The frequency of these discrete intervals has been chosen as a function of the number of analog solution points.
  - The value of the sourced power was determined by:
    - Maximum power between successive sourcing events.
    - Average power dissipated in the same intervals.
    - Power at the last sampling point.

Implementation, Cont.
—Electrothermal Semiconductor Models

- **When statements section**
  - Used for discrete time simulation.
  - Contains event-dependent assignments and scheduling.
- **Values section**
  - Used to define the primary algebraic relationships and variables that are to be extracted during post-processing.
  - The temperature-dependent property of the linear self-heating resistor is implemented.
- **Equations section**
  - Describes the terminal characteristics of the model.
  - The governing equation of the resistor and power dissipation sourced out of a thermal node is implemented.

```
# The ret_e template models a linear # self-heating resistor

template ret_e p m th st = r0, alpha, t0,  nstep

# Thermal node
thermal_c            th
# Electrical nodes
electrical           p, m
# State node
state nu  st
# Arguments
number     r0 = 1,
           alpha = 0,
           t0 = 27,
           nstep = 1
# Template body
{
# Local declarations
state p p_last1, p_last2, p_now, pwrt
val p pwr,power
val r res
state nu count=0
# DC initialization
when (...) {
           ......
           }
```

```
# Convert an analog signal to an
# analog event-driven signal
when(...){
......
}
values{
# Temperature-dependent property of a #linear self-heating resistor
res=r0*(1+alpha*(tc(th)-t0))
# Calculation of power dissipation
          pwr=v(p,m)**2/res
# DC algorithm
          if (dc_domain) power=pwr
          else power=pwrt
}
equations {
# Governing equation for a resistor
          i(p->m) += v(p,m)/res
# Power dissipation sourced out of thermal node th
          p(th) -= power
}
}
```

Fig. 2. Psuedo-template of a resistor with linear self-heating

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Implementation, Cont.

—Thermal Models

- **Thermal networks consist mainly of thermal resistance and thermal capacitances**
  - The thermal models are typically lumped approximations of the heat flow.
  - All materials exhibit some resistance to heat flow as well as a capacity to store heat.
- **A psuedo-template of an event-driven thermal capacitance**
  - Two thermal nodes and one state node.
  - The state node is used to connect the state nodes of the electrothermal models.
  - When an event is scheduled on the state node, the temperature of the model will be reevaluated.

```
# Template of thermal
capacitances
# Template header and
# header declarations
template ctherm_ev th tl
st = cth
# Thermal nodes
 thermal_c th, tl
# State node
state nu st
# Arguments
number cth = 0.0001
# Template body
{
# Local declarations
          var p pwrc
          state p
pwrc_last=0
          state nu
last_time=0
          state tc deltc0
          val tc deltc
```

```
# DC initialization
when (…) {
          ……
          }
# Event-driven algorithm
when(event_on(st)) {
……
          }
# DC algorithm
values{
……
          }
# Governing equation for
thermal
# capacitances
equations{
          p(th->tl) +=
pwrc
          pwrc:tc(th,tl)=
deltc
          }
}
```

Fig. 3. Psuedo-template of event-driven thermal capacitance

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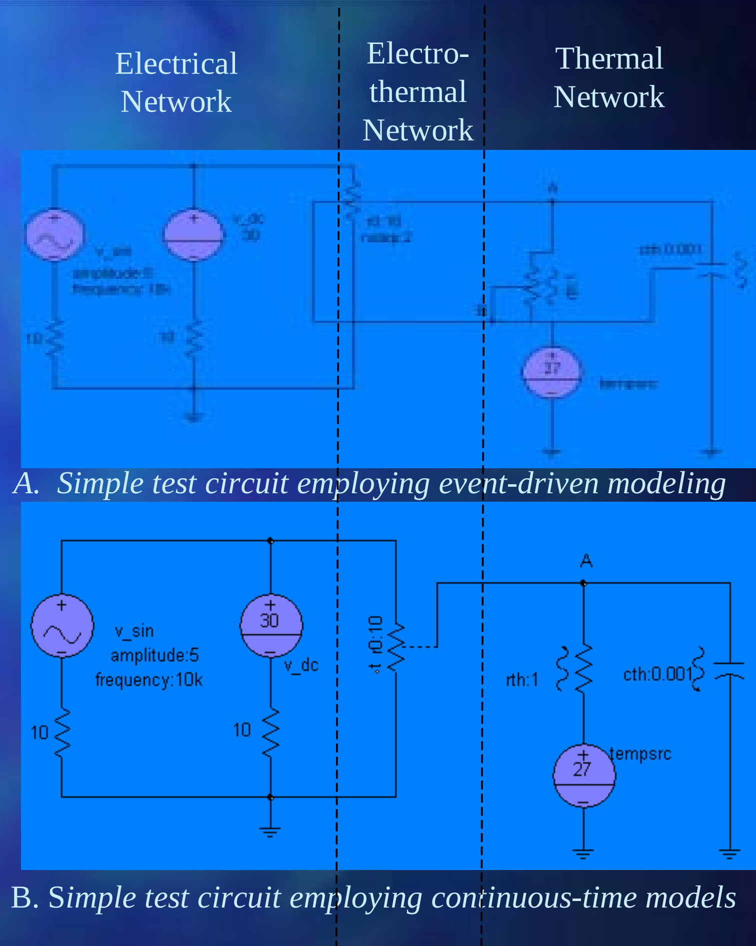
Simulation Results

- Event-driven modeling circuit (Fig. 4A and analog modeling circuit (Fig. 4B).
- Analog Node *A*:
  - connection point of thermal models and electrothermal models.
  - Power dissipation at node *A* is calculated once every certain time points.
- State Node *B* :
  - Functions as a control signal.
  - When power dissipation is updated, an event will be triggered on node *B*, and the temperatures at node *A* will be reevaluated.



A. Simple test circuit employing event-driven modeling

B. Simple test circuit employing continuous-time models

Fig. 4. Simple Test Circuits

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Simulation Results, Cont.

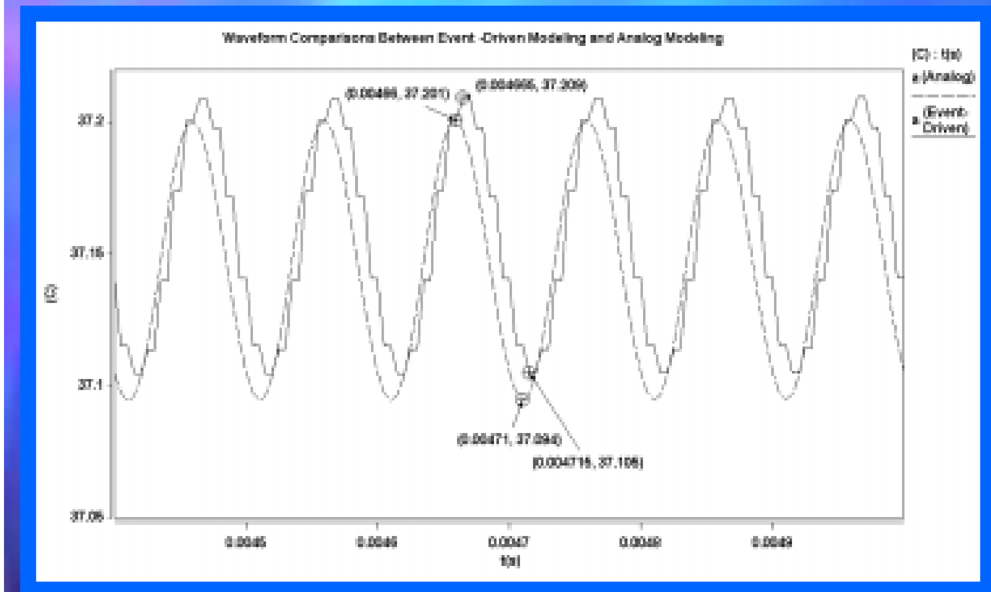

Fig. 5. Simulation Results —expanded view.

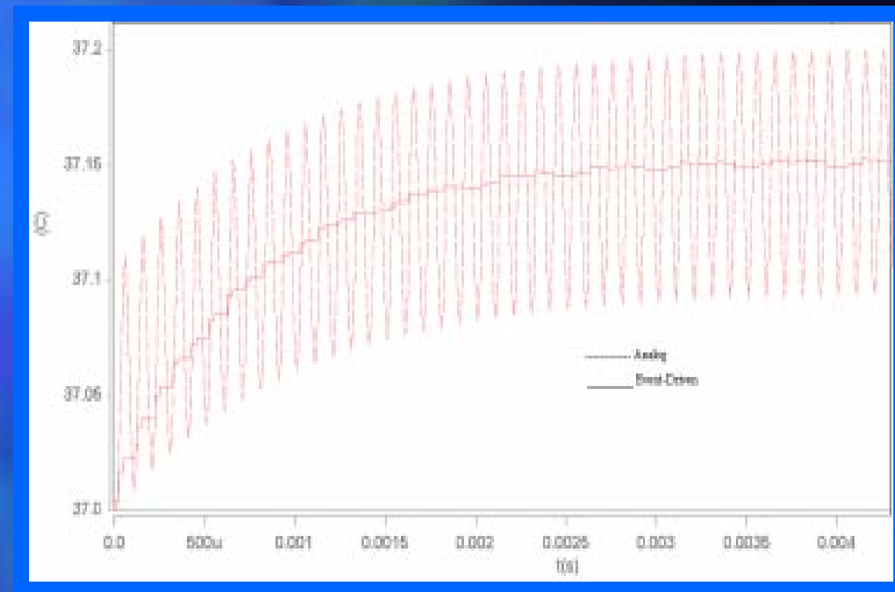

Fig. 6. Simulation Results —stead- state comparison.

- Instantaneous and steady-state cases.
  - Temperature evaluation every 5 analog solution points (Fig.5).
  - Temperature evaluation every 50 analog solution points (Fig. 6)
- Simulation speed comparison

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Conclusion

- Event-driven modeling technique in electrothermal effects simulation has been presented.
- Proven to be sufficiently accurate in both instantaneous and steady-state cases.
- Allows for selective adjustment of the accuracy at a model parameter level.
- Future work
  - Investigation into the possibility of combination of two techniques (frequency/time domain model reduction technique and analog event-driven modeling technique)
  - Development of a method for extraction of event-driven thermal models from layout.

Questions?

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