Event-Driven Electrothermal Modeling of Mixed-Signal Circuits[1]

Xiaoling Huang
Department of Electrical Engineering
University of Arkansas
Fayetteville, AR 72701
xxh03@engr.uark.edu

H. Alan Mantooth
Department of Electrical Engineering
University of Arkansas
Fayetteville, AR 72701
mantooth@engr.uark.edu

Abstract

This paper describes a novel modeling methodology for electrothermal effects in large mixed-signal circuits. It is accomplished by developing analog event-driven electrothermal and thermal models in an analog hardware description language (AHDL). The large-scale mixed-signal circuits represented by the analog event-driven models can be analyzed more efficiently than using standard analog models.

Keywords

Electrothermal, Analog Event-Driven Modeling, Thermal Modeling, Mixed-Signal Modeling

1. Introduction

As mixed-signal circuits and systems become more complex, the design and test issues become increasingly difficult to manage. One of the most significant barriers is that of full-chip design verification and test. A primary goal of the semiconductor industry is to integrate more circuits onto a single chip. One area that poses a problem in achieving this goal is designing the circuits such that heat generated by the operating circuitry is properly managed. As the feature sizes decrease, thermal interactions between devices on the same chip will increase. Moreover, although modern designs dissipate less power, they are also characterized by an increased power density. This means that the area available for heat dissipation decreases more rapidly than the dissipated power for small feature devices. Hence thermal effects will be continuously amplified. Designers are more and more aware of the fact that thermal effects, if not correctly estimated at the early design phases, may cause a failure of the designed chip to meet performance requirements, resulting in a serious increase in design costs and delays.

Many investigations have been conducted into electrothermal effects that occur in semiconductor materials and microelectronic circuits. As a result, several methods for modeling these effects have been developed. The two most prevalent methods are finite-element analysis at the device level and lumped-element, continuous-time approximations at circuit level. Finite-element simulation is used to study individual device heating, but while highly accurate, it is too computationally expensive to be of value for large-scale circuit design. The lumped-element method is more suitable for circuit design. It has focused on the development of compact models that accurately model the physical effects of heat moving through the semiconductor material, chip package, and heat sink. These models have been developed in such a way that they are coupled to the electrical devices themselves in order to model dynamic heating or self-heating.

The semiconductor heats up as devices conduct current. However, the electrical device model's current is a function of temperature, the current changes as the temperature increases. The lumped-element method effectively captures the heat diffusion through solid materials according to the heat diffusion equation. Novel work in dynamic thermal analysis of IGBTs was reported in [1] and [2]. This work and subsequent investigations led to a more generalized method of creating compact dynamic thermal models and compact dynamic electrothermal semiconductor models [1],[3]. In dynamic thermal analysis, temperature is treated as a time-varying quantity during the simulation analysis as opposed to a constant. This offers the possibility of analyzing any feedback mechanisms from thermal to electrical as devices operate. One disadvantage of the lumped-element method is that the simulation times become exorbitant if more than a few devices and thermal effects are modeled in this way. If this approach were applied to modern mixed-signal circuitry, the simulation times would be unacceptable.

In order to simulate large-scale circuits with an acceptable accuracy and at a reasonable speed, various reduced-order modeling techniques, such as PACT [4], MPVL [5] and PRIMA [6], have been applied. However, these frequency-domain model reduction techniques are not effective at handling complex multi-port networks with

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large port counts. Recently, a mixed frequency/time domain multiport network reduction method that is specially optimized for reducing the lumped 3D thermal network for modeling substrate heat conduction has been presented in [7]. While maintaining the accuracy and passivity of the reduced system, the method is especially useful for performing full-chip transient electrothermal simulation for reliability or temperature-induced signal integrity analysis. The reduced-order modeling techniques are not discussed in this paper, but they will be included in our future work.

As mentioned earlier, the lumped-element, continuous-time dynamic thermal models increase the complexity of simulations to a point that this type of analysis can become quite unwieldy. A new method of dealing with this issue is to model the temperature as an event-driven analog entity. An event-driven entity is one that changes at discrete times. In contrast to a digital signal that has a finite, quantized number of values (i.e., logic 1, 0, X, Z, and maybe other strengths), an analog event-driven signal can take on any value in the number continuum. Analog event-driven signals are often referred to as discrete-in-time, continuous-in-value signals.

The focus of this work is on improving simulation efficiency by applying analog event-driven modeling techniques in electrothermal simulation. The previous electrothermal network simulation work is briefly reviewed in Section 2. Section 3 details event-driven modeling techniques, and provides some simulation results. Finally, conclusions are provided in Section 4.

2. Electrothermal Network Simulation

A typical electrothermal simulator, as conceptualized in the diagram in Fig. 1, 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 the device power consumptions.

In standard continuous-time simulation, all models are analog. In the mixed-signal simulation technique proposed here, electrical models remain analog while some of electrothermal and thermal models are event-driven.

2.1 Electrothermal Network

In an electrothermal network the power dissipated in a device is directly fed into the thermal network through a thermal node. In other words, each dissipative device acts as a power source in the thermal network. In return, the temperature at the thermal node of a device is the operating temperature of the device. This permits the device model to adjust its behavior as a function of its operating temperature. This is known as dynamic thermal analysis.

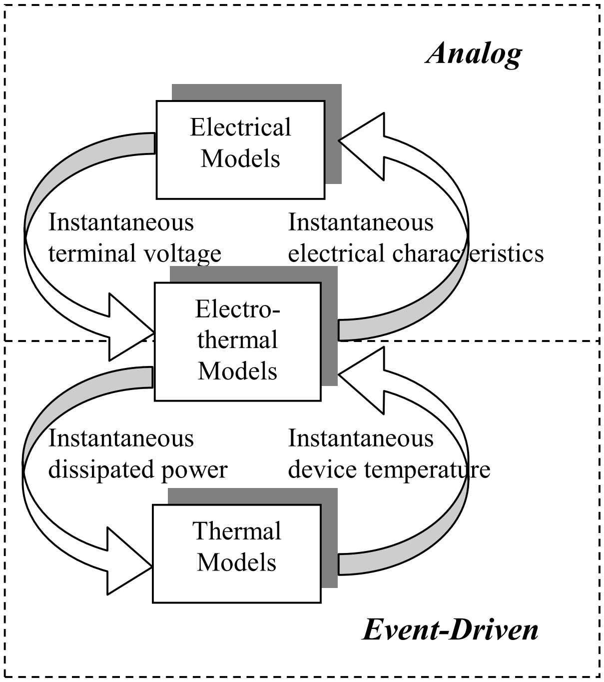


Fig. 1. Block diagram of a proposed event-driven electrothermal simulation approach.

The electrothermal semiconductor device models interact with the thermal and electrical networks through the electrical and thermal terminals, respectively [2]. The electrothermal semiconductor models use the instantaneous device temperature (temperature at the silicon-chip surface) to evaluate the temperature-dependent properties of silicon and the temperature-dependent model parameters. These temperature-dependent values are then used by the physics-based semiconductor device model to describe the instantaneous electrical characteristics and instantaneous dissipated power. The dissipated power calculated by the electrical model supplies heat to the surface of silicon-chip thermal model through the thermal terminal.

2.2 Thermal Network

Heat diffusion through solid materials is modeled by sourcing dissipated power into a thermal network, which represents the material properties (i.e., thermal resistance and capacitance). The temperature profile is the result of heat flow in a thermal network. Energy conservation dictates that the sum of all power contributions at a thermal node equal zero, and that the temperature at all terminals connected to a thermal node be identical. The notion of a conservative system as it relates to simulation can be generalized by referring to two entities: through variables and across variables. An AHDL model associates a through and an across variable with each connection point in the model. In general, the through variables are summed to zero at a connection point as a means to insure a conservative system. In a thermal network power is the through variable and temperature is the across variable. Thus, the simulator solves for the dynamic temperature distribution within the thermal network in the same way that node voltages are solved for within an electrical network. Due to this generalization of conservation, it is straightforward to implement both electrical and thermal systems simultaneously from a simulation standpoint.

The thermal network is represented as an interconnection of thermal component models. Thermal component models that model the heat diffusion through materials are passive in nature. No power is sourced from them. Collectively, they can be thought of as networks of thermal resistances and capacitances.

3. Implementation

The time constants in a typical thermal network (i.e. for heat flow within the silicon chip, package, and heat sink) are many orders of magnitude longer than the time constants in the accompanying electrical network. It is therefore possible to retain accuracy in the solution of the thermal network by evaluating the temperature less frequently than would be done in a coupled electrothermal analog simulation. To accomplish this, the technique employed represents the thermal network as an event-driven network. This eliminates the stiffness in the analog equations that arise from the presence of the thermal network. While it's true that mixed-signal simulation run times are mostly dictated by the analog portion being simulated, the transformation of some of the analog portion to the event-driven portion can improve the overall simulation times.

Analog models are still used for electrical devices. For electrothermal components, the thermal signals of the model will be approximated by analog event-driven signals, which only change value at specified intervals. At each interval boundary the temperatures will be reevaluated based on the latest power dissipation values. Any electrothermal effects that result from the updated temperatures will be evaluated at the next solution point of the continuous-time network. Finally, the thermal component models are entirely event-driven. They are activated when a control signal from electrothermal device models triggers them.

In order to implement the technique described above, some analog event-driven electrothermal device and thermal component models were developed.

3.1 Electrothermal Semiconductor Models

The electrothermal models for semiconductor devices couple electrical and thermal networks. The electrical terminals of these models are connected to the electrical network and their thermal terminal is connected to the thermal network. The development of self-heating

```
# 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. Template of a resistor with linear self-heating.

semiconductor models using the analog technique requires modeling the power dissipation in devices and "sourcing" this power out of a thermal node.

In the analog event-driven modeling method, the power dissipation is computed for active devices as before, but the "sourcing" of the power is performed at discrete intervals rather than continuously. The frequency of these discrete intervals has been chosen as a function of the number of analog solution points (e.g., one "power sourcing" for every 10 analog time points). Furthermore, the value of the sourced power is the instantaneous dissipated power with one exception. The exception is that if a local maximum power dissipation is achieved, then this value is sourced immediately upon detection (i.e., with a delay of one time point) independent of the fixed interval.

There are only a few basic items that must be addressed to implement self-heating effects in a semiconductor model. A simplified template of a linear self-heating resistor described in Fig. 2 outlines these items. They are described from top to bottom as the template is listed. However, the order of the sections (i.e., when statements, values, equations, etc.) is arbitrary. The when statements section are used for discrete time simulation. It contains event-dependent assignments and scheduling. The values section is used to define the primary algebraic relationships in the model and variables that are to be extracted during post-processing. In this pseudo-template, for instance, the temperature-dependent property of the linear self-heating resistor is implemented in the values section. Lastly, the equations section describes the terminal characteristics of the model. This is where, the governing equation of the resistor and power dissipation sourced out of thermal node is implemented.

As shown in Fig. 2, the model of linear self-heating resistor has four nodes: two electrical nodes, one thermal node and one state node. The electrical nodes are used to connect electrical network and the thermal node is used to connect thermal network. The state node is used for controlling the temperature updates of thermal network.

3.2 Thermal Models

The thermal models are typically lumped approximations of the heat flow through the chip, package, or heat sink material. All materials exhibit some resistance to heat flow as well as a capacity to store heat, expressed by their specific heat. Therefore, thermal networks consist mainly of thermal resistance and thermal capacitances (representing chips, packages, heat sinks, and ambient), together with power and temperature sources.

A pseudo-template of an event-driven thermal capacitance is described in Fig. 3. The function of each section is similar to that of linear self-heating resistor described in section 3.1. The model of the thermal capacitance has three nodes: 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 by a semiconductor device, 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.

The template of thermal resistance is similar to that of thermal capacitance except for the governing equations.

3.3 Simulation

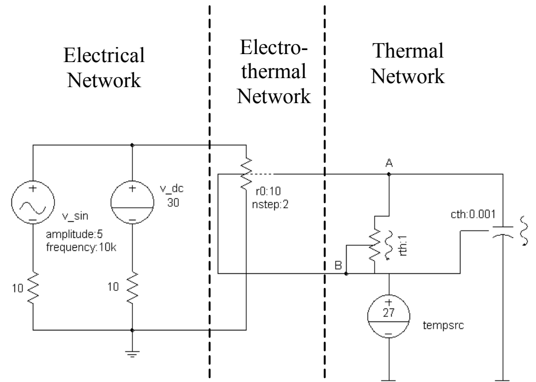
The developed event-driven electrothermal and thermal models were simulated using the Saber simulator [8]. The simulations were performed on a set of test circuits. Fig. 4 is a simple test circuit. Event-driven models and analog models are used in Figs. 4(A) and 4(B), respectively. Node *A* is the connection point of thermal models (a thermal resistance and a thermal capacitance in this circuit) and electrothermal models (a self-heating resistance in this circuit). Node *B* in Fig.4 (A) is a state node. It functions as a control signal for triggering the evaluation of the thermal network.

The power dissipation at node *A* is calculated once every certain time points. When power dissipation is updated, an event will be triggered on node *B*, and the temperatures at node *A* will be reevaluated.

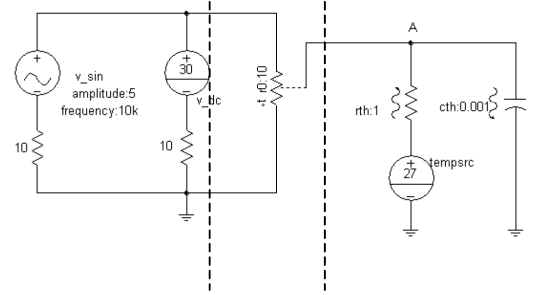
Both the event-driven circuit and the analog circuit in Fig. 4 were simulated. The simulation results are compared in Figs. 5 and 6. In Fig. 5 the event-driven simulation is run with a temperature evaluation every 5 analog solution points. Although there is some waveform delay (about 5 μs for this circuit) in the event-driven simulation, the percent difference of average magnitude between the event-driven simulation and analog simulation is only 0.0256%.

In Fig. 6, the temperature evaluation is performed every 50 analog solution points in order to simulate steady-state thermal behavior (as opposed to instantaneous). The waveforms illustrate this envelope response.

It is not very insightful to compare the simulation speed for such a simple circuit as Fig. 4. The overhead of event-driven simulation in Saber is enough to make the event-driven results equal to or slower than the pure analog. Future work involves investigation of larger, more complex circuits and use of simulation technology more adept at event-driven evaluation.



A. Simple test circuit employing event-driven modeling



B. *Simple test circuit employing continuous-time models*

Fig. 4. Simple Test Circuits

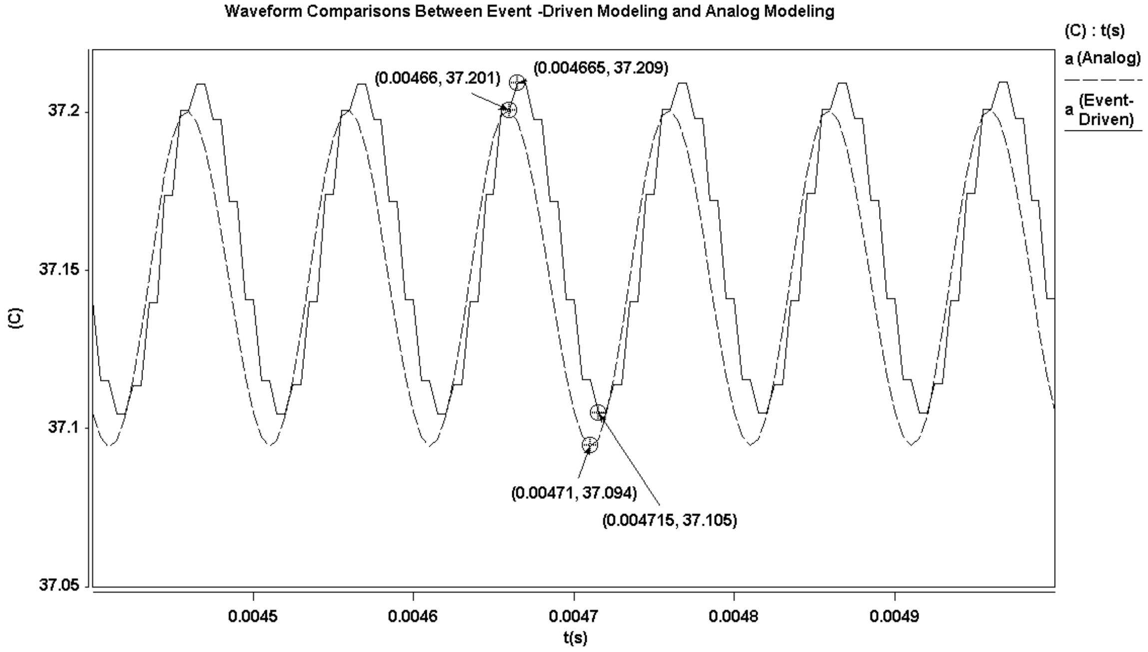


Fig. 5. Simulation Results — expanded view.

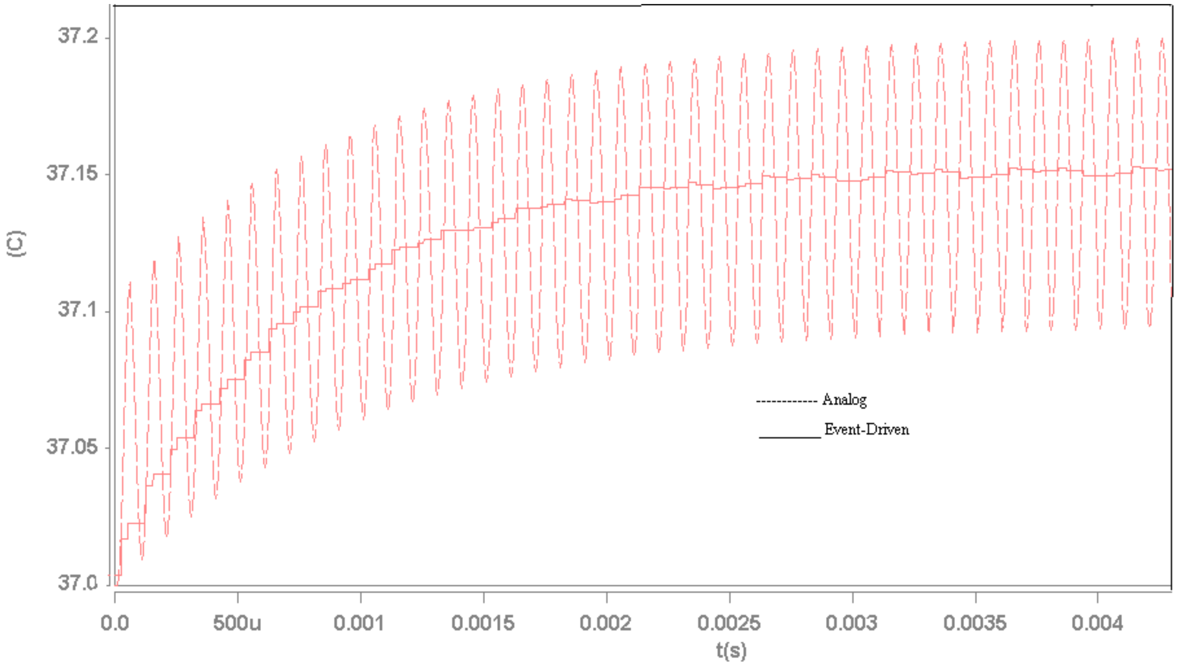


Fig. 6. Simulation Results —steady- state comparison.

4. Conclusion

We have presented an event-driven modeling technique in electrothermal effects simulation. Compared to the analog method, the simulation results of the analog event-driven method have been proven to be sufficiently accurate in both instantaneous and steady-state cases. Further, the technique allows for selective adjustment of the accuracy at a model parameter level.

Future work includes some investigation into the possibility of combination of two techniques (frequency/time domain model reduction techniques and analog event-driven modeling techniques), and developing a method for extraction of event-driven thermal models from layout.

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