Reliability of On-Chip Systems
- A Thermal Perspective -

by J. Henkel
Outline

- Dependability Problems
- Dependability and Thermal Issues
- Counter Measures
- Thermal Management
Outline

- Dependability Problems
- Dependability and Thermal Issues
- Counter Measures
- Thermal Management
In the Past ...

... Moore’s Law provided a win-win situation:

- Smaller feature size
- Higher integration density, more functionality
- Lower power consumption
- Higher speed (performance)
- Less cost (per-transistor costs)
  
...
In the Future …

- Problems
  - Complexity: In 2017 100 Billion Transistors on chip
  - Productivity gap
  - Thermal problems
  - Increasing relevance of aging effects
  - Manufacturing defects, process variation
  - Stochastic effects since physical limits are reached
  - Decreasing yield

Reliability

---

J. Henkel, Keynote ISVLSI, 2011, July 4th, Chennai, India
Technology Nodes

Manufacturing  Development  Research

90 nm  2004
65 nm  2006
45 nm  2008
32 nm  2010
2012+

SiGe S/D
Strained Silicon

SiGe S/D
Strained Silicon

50 nm
35 nm
30 nm
20 nm
10 nm
5 nm

Metal Gate
High-k
Si Substrate
Tri-Gate
Nanowire
Carbon Nanotube FET

(Src: S. Borkhar, DAC'07)
Variabilities

- Variability of transistor structures
  - Channel Length
  - Isolators thickness (gate oxid) gate <-> transistor channel
  - Randomized Dopant Fluctuations (RDF) -> Threshold voltage
    => Decreasing mobility
    => Increasing leakage

- Counter Measures
  - Strained Silicon Engineering
    - Strain channel to increase mobility
  - „High-K“ materials for gate isolation (e.g. Hafnium)
    - May increase aging

...
Aging Effects

- Elektromigration (EM)
- Stress Migration
- Time-dependent Dielectric Breakdown
- Dependent upon operating temperature
- Through technology scaling
  - Increasing frequency
  - Increasing power dissipation per area, volume

Wire affected by electro migration

Power density [W/cm²]

Technology nodes [nm]
Increasing Susceptibility to Soft Errors

- Ionizing rays may change charge concentration
  - (like He$^{2+}$)
  - => may lead to bit flips

- α-rays
  - Radioactive decomposition of non-pure chip material
  \[ \frac{A}{Z}X \rightarrow \frac{A-4}{Z-2}Y + \frac{4}{2}He \]

- Cosmic rays (particularly neutrons)
- accelerated through technology advancements
  - Low voltage and capacitances
  - Representation of bits through smaller and smaller charges

 transient errors through neutrons

\begin{align*}
8 \text{ percent degradation/bit/generation}
\end{align*}
Particle strikes: causing soft errors

(Src: R. Mastipuram: Cypress Semiconductor @ EDN, Design Feature’04
Soft errors’ impact on system reliability)
Outline

- Dependability Problems
- Dependability and Thermal Issues
- Counter Measures
- Thermal Management
Heat Remains a Problem

“Circuit heat generation is the main limiting factor for scaling of device speed and switch circuit density”

By Jeff Welser, Director SRC Nanoelectronics Research Initiative, IBM, Opening Keynote Address ICCAD 2007

From Power to Temperature

- Heat is thermal energy [Joule]
- Heat transfer $Q$ [Joule/s]
- Heat flux is heat transfer rate through given surface area
- Thermal capacity $C$:

$$C = \frac{\Delta Q}{\Delta T}$$

- Temperature $T$ reflects the amount of heat energy given a certain material

<table>
<thead>
<tr>
<th>Material</th>
<th>$c=C/\text{dm}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>1.55</td>
</tr>
<tr>
<td>Cu</td>
<td>3.45</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>4.17</td>
</tr>
<tr>
<td>Air</td>
<td>0.0012</td>
</tr>
</tbody>
</table>
From Power to Temperature (cont’d)

Basic temperature equation:

\[ C \frac{dT}{dt} = -Q + P \]

\[ T(t_1) = T_0 + \frac{1}{C} \int_{t_0}^{t_1} -Q(t) + P(t) \, dt \]

where \( Q \) is the heat dissipation rate.

\[ T(t) = T_0 - (T_{SS} - T_0) e^{-\frac{t}{h}} \]

**Heating**

\[ T(t) = T_0 + (T_0 - T_A) e^{-\frac{t}{c}} \]

**Cooling**

- \( T_{SS} \) is the steady state temperature the system will asymptotically reach with current power configuration.
- Ambient temperature \( T_A \) is minimum reachable temperature.
Thermal Distribution and Dynamics

- Example showing localized computation switching between two areas on the chip

Src: Henkel, Ebi, Amrouch
Thermal Distribution and Dynamics (cont’d)

- Example: Xilinx Virtex 5 running a web server application
From Temperature to Reliability

- For instance: Electromigration:
  - directly linked to temperature
    - Basic Mean time to failure modeled by Black’s Equation:
      $$MTTF = Aj^{-n}e^{\left(Q \over kT\right)}$$
    - $MTTF$ decreases exponentially with temperature
      → Goal: reduce peak temperatures
From Temperature to Reliability

- MTTF also affected by thermal gradients

Spatial gradients
Simulated Thermal map Pentium M
[L. Finkelstein, Intel 2005]

Temporal gradients
[K. Skadron, 2005]

→ Goal: balance temperatures
Thermal/Heat Problems in 3D

- 3-D chips especially problematic

3-D structures

(Src: Y. Xie, PennState)
Thermal/Heat Problems in 3D Architectures

- **Problem**: vertical heat flow
  - Only one layer directly interfaces with the heat sink
  - Heat needs to dissipate through multiple layers

- The heat sink is located on top of the chip
- Hot cores distant to the heat sink dissipate their heat through other layers
- Silicon has a low thermal conductivity!
  - 150 W/(m*K) (Silicon)
  - 401 W/(m*K) (Copper)
Outline

- Dependability Problems
- Dependability and Thermal Issues
- Counter Measures
- Thermal Management
Counter Measures at Device Level

FinFET-Transistor
- Idea: reduce channel thickness
- But: reduced mobility

Graphene-Transistor

CNFET-Transistor
- Idea: combine high mobility and thin channel width
- But: problems in placement and structural growth

Spin-Transistor

Injection of spin-polarized electrons at source V-gate affects spin trace electron current only when electron spin parallel to drain-spin
- Idea: low power dissipation
- But: hard to control => high error rates

NanoPLA block and 3D Interconnect

Source: DeHon

Single-Electron Transistor
A Spectrum of Solutions

- **Near and medium term solutions:**
  - Massively parallel, modularity (cells, blocks)
  - Regularity (grid processing, cellular arrays)
  - Locally connected (near-neighbor connections, crossbar)
  - Higher functionality (multiple valued logic, threshold logic)
  - Adaptivity through Reconfigurability
  - Asynchronous (including GALS)
  - Fault-tolerance (noise immune, redundant, self-testing, self-correcting)
  - Defect-tolerant (reconfigurable)
  - Redundant, adaptive (self-adaptive, self-organizing, evolvable)
  - Bio-inspired, autonomous computing etc.
  - Nanophotonic (optical communication, GOLE)
  - Nanofluidic
  - 3D interconnects
  - Probabilistic (algorithms, encoding, communication)

- **Long term solutions:**
  - Molecular, quantum
  - Quantum-dot cellular automata
  - Adiabatic / reversible
  - …

(Src: M. Huebner, KIT)
Idea: use Principles of Bio-inspired/Autonomous Computing

- Organic Computer Systems
  - will possess lifelike properties.
  - will consist of autonomic and cooperating sub systems and will work, as much as possible, in a self-organized way.
  - will adapt to user needs,
  - will be controlled by objectives ("goal-driven"),

- Self-organization allows for adaptive and context aware behavior:
- Self-X
  - self-configuring
  - self-optimizing, self-adapting
  - self-healing
  - self-protecting
  - ...

(Src: H. Schmeck, KIT)

=> Beneficial for reliability
Self-Organization

Under appropriate conditions the collaboration of simple agents may produce highly complex, adaptive systems.
No necessity for central control.

Examples: (Src: H. Schmeck, Uni Karlsruhe)
- Termite / Ant colonies
- Swarms of bees
- Economy
- Traffic
- Internet

Idea: Complexity management by self-organization.
But: Who is managing/controlling self-organisation?
Emergent Phenomena

- Local interaction may lead to entirely new global properties.

  "The whole is more than the sum of its parts!"

- Emergent effects may be desired or undesired
  - How can we generate positive emergence?
  - How can we prevent negative emergence?

- Examples:
  - "green wave" at traffic lights
  - deadlock / lifelock
  - ant roads

- Can we use emergent Phenomena for computing systems?

(Src: H. Schmeck, Uni Karlsruhe)
Challenges in Bio-inspired/Autonomous Computing

- Provide systems with sufficiently large degrees of freedom for adapting to different requirements.
- Systems have to be aware of
  - what type of service they can provide,
  - what type of service they need from others,
  - what the current environment wants to get done.
- Systems should have a “desire” to be active (incentives?).
- Systems should be robust with respect to external changes
- Systems should react flexibly to changing external constraints
- There will be a need for “controlled self-organization”.

(Src: H. Schmeck, Uni Karlsruhe)
Bio-inspired/Autonomous Computing

Self-organizing computing systems are becoming a key topic for academic and industrial research.

So, what do we need?
- Nature inspired methods, Artificial Life:
  - Evolutionary Algorithms, Ant Colony Optimization, Swarm intelligence
- Multi-Agent systems
- Cognitive systems
- Learning
- Observer/Controller-Architectures
- Results from control theory (model predictive control??)
- Reconfigurable computing systems
  
  (Src: H. Schmeck, Uni Karlsruhe)

Organic/Autonomous Computing may help to build more reliable systems!
Outline

- Dependability Problems
- Dependability and Thermal Issues
- Counter Measures
- Thermal Management
  - Using principles of self-organization:
    - Scalability
    - Proactivity
    - No single point of failure
Spreading tasks throughout the chip reduces thermal hotspots
Motivation

Open Problem
Thermal hotspots in multi/many-core architectures

Possible Solution:
Dynamic Thermal Management (DTM)
- Design-time techniques may not predict the behavior a priori
- Runtime application mapping algorithm may be used to homogeneous thermal distribution

What Properties are Required?
- Scalability
- Proactive behavior
- Light-weight in terms of hardware/software
Idea: use Agent-Based System

“An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors “

Desired properties of agent

- **Situated** ↔ Software/hardware entity in each tile
- **Scalable** ↔ Agents act locally
- **Proactive** ↔ Triggered before threshold is reached
- **Social** ↔ May negotiate with their neighbors
- **Reactive** ↔ React to outside stimuli (i.e. to thermal sensors)
- **Light-weight** ↔ Require small memory/computation footprint
Agent-Based System

Approach
- Economic policy to achieve proactive behavior
- Distributed approach for mapping using agents

Power Trading Agents
- Economic policy (supply/demand) to achieve proactive behavior
- HW/SW implementation
- Situated in each tile

Mapping Agents
- Distributed approach for mapping using agents
- SW implementation
- Responsible for a region of neighboring tiles
- Can be migrated
Agent-Based System

Power trading agents in every tile
Agent-Based System

Neighbours are all adjacent tiles with direct communication links
Agent-Based System

Mapping agents in a region of Neighboring tiles

Region 1

Region 2
Units traded between agents are power units.

- **Used** power units: used to run tasks refer to a certain voltage/frequency setting.
- **Free** power units: can be freely traded among agents.

Number of power units \( \rightarrow \) frequency \( f \), voltage \( V \) tasks can be run.
Assumptions, Parameters

Tasks have fixed deadline
A worst case of the execution time (WCET) is known
→ Minimum frequency is set for a tile
→ This results in the number of ‘used’ power units

Task migration is system dependent
(measured around 100K cycles
(saving, transferring, loading task context)
Trading Rules

*Buy and sell* incentives express an agent’s “desire” to acquire/give up power units => based on “supply/demand” like in an economy
Trading Rules

- **Buy** and **sell incentives** express an agent’s “desire” to acquire/give up power units => based on “supply/demand” like in an economy.

- Incentive to **Sell**: \( sell = w_{u,s} \cdot used + w_{f,s} \cdot free \)

- Incentive to **Buy**: \( buy = w_{u,b} \cdot used - w_{f,b} \cdot free + \gamma \)
Trading Rules

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Weights and \( \gamma \) are dependant on processor type, total amount of power units, and number of tiles.

Logically: used units => *demand*
free units => *supply*
Trading Rules

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- Incentive to Sell: \( sell = w_{u,s} \cdot used + w_{f,s} \cdot free \)

- Incentive to Buy: \( buy = w_{u,b} \cdot used - w_{f,b} \cdot free + \gamma \)
  \[ buy = buy - a_b \cdot temp \]
  \[ sell = sell - a_s \cdot temp \]

**temp** is temperature above threshold \( T_0 \)
Trading Rules

- Buy and sell incentives express an agent’s “desire” to acquire/give up power units => based on “supply/demand” like in an economy

- Incentive to Sell: \( sell = w_{us} \cdot used + w_{fs} \cdot free \)

- Incentive to Buy: \( buy = \sum p_i \cdot \text{task}_i \)

- Sell incentive must also consider running tasks:

\[
sell = sell - \sum p_i \cdot \text{task}_i
\]

- Agent of tile \( n \) sells to neighbor \( i \) if:

\[
(sell_n - buy_n) - (sell_i - buy_i) > \varepsilon
\]
Agent-Based Power Trading

Task is mapped to tile with insufficient power units
Agent-Based Power Trading

Agent trades power units with neighbors using cost function

\[(sell_n - buy_n) - (sell_i - buy_i) > \varepsilon\]
Agent-Based Power Trading

Temperature increase may trigger new trading
Power Unit Propagation

Agent 1  Agent 2  Agent 3  ...  Agent n

Update values  Update values  Update values  ...  Update values

sell  Update value  sell  ...  Update value

Agent negotiation interval

Update values  Update values  Update values  ...  Update values

sell  Update value  sell  ...  Update value

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Power Unit Propagation

- Agent negotiation interval > 100µs
- Maximum temperature increase 0.1°C

But: What happens when there are no free units to acquire or sell incentive is high (e.g. due to high temperature) etc.?

Application (re-)mapping is triggered
Task (Re-)Mapping

Trading agent, src
- power units traded
- not enough power units!

Trading agent, dest
- get units
- buy
- task mapped successfully

Mapping agent
- application mapping
- buy/sell values
- suitable tile found
- input

Start state
End state
state

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Task (Re-)Mapping

- Triggered when tile does not have enough power units to run task
- Mapping agents realized separately from trading agents
- Buy and sell values input to mapping agents
- Power trading agent of destination tile may require additional units
- Task mapped to tile where 
  \[(sell_n - buy_n) - (sell_i - buy_i)\] is maximal as long as buy value is not negative.
Agent-Based Power Trading
Example

a) Temperature for one task (task1) at time t1

b) Temperature for two tasks at time t2

c) Five tasks at time ti

d) Task1 (re-)mapped at time ti+1

<table>
<thead>
<tr>
<th>time</th>
<th>t0</th>
<th>t1</th>
<th>t2</th>
<th>t_i</th>
<th>t_i+1</th>
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<tbody>
<tr>
<td>free</td>
<td>sell</td>
<td>used</td>
<td>buy</td>
<td>used</td>
<td>buy</td>
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</tr>
</tbody>
</table>

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ces.itec.kit.edu
Scalability of Agent Communication

Power trading

- Centralized power trading
- Using TAPE

(Re-)mapping

- 2 mapping agents
- 4 mapping agents
- 8 mapping agents
Scalability of Agent Communication

- **Power trading**
  - Centralized power trading
  - Using TAPE

- **KB / power trading interval**

- **KB / system state update**

- **Total tiles**

- **Mapping agents**
  - Communication ↑
  - Lower communication effort

- **But: too many mapping agents have opposite effect!**
Results: Peak Temperature

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>No Dynamic Thermal Management</th>
<th>Our TAPE approach</th>
</tr>
</thead>
<tbody>
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<tr>
<td>lame</td>
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<td>pgp</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>multiple II</td>
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</tbody>
</table>

Peak Temperature (°C)
Agent Implementations

- Implemented in Software
  - Compete with tasks for computation
  - Are not always possible (e.g. in dedicated hardware)

- Implemented in Hardware
  - Can be realized on any tile
  - Does not take processing time away from tasks
  - Require additional area (143 slices in Xilinx Virtex-4 FPGA)

<table>
<thead>
<tr>
<th>slices</th>
<th>LUTs</th>
<th>Flip-flops</th>
<th>Mult</th>
<th>Max Freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>143</td>
<td>276</td>
<td>84</td>
<td>2</td>
<td>148.9MHz</td>
</tr>
</tbody>
</table>

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Hardware Demonstrator

- Hardware prototype in running on a Xilinx Spartan3e FPGA with 4 Picoblaze tiles
- Thermal sensors realized through ring oscillators

Watch LEDs
System Setup

- Microblaze Tile
- Empty-Tile
- I/O-Tile

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System Setup

- On-chip memory very limited: only max. 16KB per tile
- We require a lightweight OS running on each Tile
  - FreeRTOS: embedded OS;
  - kernel size: 4K-9K
    [www.freertos.org]
Thermal Camera for accurate thermal Evaluation

- DIAS Pyroview IR Camera
  - Spatial resolution macro lens: around 50µm
  - Limited by camera IR spectral range of 8µm - 14µm
  - Temperature range configurable: -20 °C to 120 °C or 0°C to 500°C
  - Sampling rate of 50Hz
    - Camera transmits 50 frames per second over ethernet in real time
  - 384x288 pixels
  - Comprehensive SDK for accessing camera functionality
System Setup
Summary

- Reliability is a problem when migrating to upcoming technology nodes
- MTTF of certain effects are related to temperature
- Dynamic Thermal Management techniques are necessary
- Important features:
  - Scalability -> for many core systems with 100s of cores
  - Single point of failure for DTM should be avoided
- Principles of self-organization may be a solution
Thank you for Attention!
Infrared Measurements and Emissivity

- Emissivity can be a problem for infrared measurements
  - Ideal “black body“ has emissivity of 1
  - Polished metal can be as low as 0.01
  - Emissivty of Silica: 0.9 - relatively high, but not optimal

- Low emissivity results in high reflection of surrounding temperatures

[Image of infrared measurement showing temperature differences]

- Metal packaging measurements very inaccurate
- Paint of logo has high emissivity (around 0.92)
- Masking tape (emissivity 0.95) covering half of chip shows actual temperature

[Emissivity table of various materials: www.omega.com/temperature/z/pdf/z088-089.pdf]
Results: Execution Time

Simulation setup

- HotSpot
- TAPE
- Sim - Panalyzer

Power units, Task mapping

Dynamic temperature threshold greatly reduces execution time (44%) due to less frequent task migrations.

Task migration penalty is 100K cycles (saving, transferring, loading task context)
Results: Execution Time

Benchmark

No Dynamic Thermal Management  Our TAPE approach  HRTM  PDTM

Execution time (s)

sha  lame  pgp  multiple I  multiple II
Agent-Based Power Trading

Agents are triggered at discrete intervals $\Delta t$

Trading done in a loop

Temperature

At discrete intervals $\Delta t$

From neighbors

To Neighbors

Current buy

Update

Agent-based power trading algorithm:

1. Task priorities
2. Value modifiers
3. Diff
4. Update
5. Neighbor buy/sell value table
6. Min
7. Sell
8. (free units > 0)?
   - Free units --: Used units --

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Results: Total Energy Consumption

Energy usage (J)

Benchmark

No Dynamic Thermal Management
Our TAPE approach

No DTM
PDTM
HRTM
TAPE

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Results: Total Energy Consumption

- Results show the sum of total system energy for all applications.
- Shorter execution times means less total energy (up to 44% less than PDTM).

Benchmark:

- No Dynamic Thermal Management
- Our TAPE approach
- HRTM
- PDTM

Energy usage (J)

- sha
- lame
- pgp
- multiple
- No DTM
Temperature and Reliability

- Process variations and electromigration can result in **hillocks** and **holes**
  - Lead to open failures or short circuit failures respectively
  - Failures may be temperature dependent due to material expansion
    - Holes may function normally at high temperatures but fail at low temperatures
    - Hillocks may function normally at low temperatures but short circuit at high temperatures

[W.D. Nix, 1992]
Temperature and Reliability

- Transient errors may result due to timing errors
  - Approx. 5% decrease in delay every 10°C temperature increase [Xie 2006]
  - Timing errors result from spatial temperature variations
    → localized hotspots need to be avoided
  - Clock trees are particularly vulnerable
    - Span across multiple thermal areas
    - Additional buffers can be inserted to cope with thermal clock skew

Clock skew compensation using a thermal management unit to control tunable delay buffers inserted into clock tree

[Chakraborty, 2008]
Temperature and Reliability

- **Electromigration**: aging effect due to transport of mass in metal interconnects
- Directly linked to temperature
  - Basic *Mean time to failure* modeled by Black’s Equation:
  
  \[
  MTTF = Aj^{-n} e^{\left(\frac{Q}{kT}\right)}
  \]

- *MTTF* decreases exponentially with temperature

  \[\Rightarrow\] **Goal**: reduce peak temperatures
Thermal issues in 3D

- Power density increases with technology scaling
  - On an average from 2W/mm² in 65nm technology to 7.2 W/mm² for 45nm [Vijaykrishnan et al. ISQED’06]

- Higher power density and temperature variation cause transient and permanent failures
  - Due to technology scaling, a drop of 66% in feature size increases the temperature from 342°C to 356°C and reduces the MTTF by 76% [Srinivasan et al. Micro’05]

- Leakage power increases with temperature
  - A change in temperature from 40°C to 120°C increases the leakage power 4 times [Li et al. NOCS’08]
Categorization of technology induced dependability effects

I. Process and design time effects
   - Yield and process variability
   - Complexity: \( > 10^{11} \) (100 billion) within a decade

II. Operation and run-time effects
   - Aging effects (irreversible)
   - Thermal effects (may speed up some ageing effects)
     - Aggressive power management may be counter-productive since thermal cycling is increased -> tradeoff
   - Soft errors
     - \( > 8\% \) increase per technology node
     - Errors are random and transient and limit exploitation of techniques like voltage scaling
Counter Measures (cont’d)

“Emerging devices are expected to be more defective, less reliable and less controlled in both their position and physical properties.”

“It is therefore important to go beyond simply developing fault-tolerant systems that monitor the device at run-time and react to error detection.”

“It will be necessary to consider error as a specific design constraint and to develop methodologies for error resiliency, accepting that error is inevitable and trading off error rate against performance (e.g. speed, power consumption) in an application-dependent manner.”

Counter Measures (cont’d)

Some further citations:


- Leon Stok, IBM: „… most variability had been hidden from the designers …This practice no longer holds for current [and future (Anm.)] technology nodes” (see p. 344 [D&T-JA08]).

- Jan Rabaey, UC Berkeley and Sharad Malik, Princeton: „Existing solutions are unlikely to scale, and we will need radically new solutions …” (see p. 299 [D&T-JA08]).

Temperature and Reliability

Black’s equation

\[ MTTF = A\omega j^{-n} e^{\left(\frac{Q}{kT}\right)} \]

Transient errors