EEC 216 Lecture #11: Power Sources

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Outline

• Power Supplies
  • Batteries and Battery Modeling
  • Fuel Cells
  • Power MEMS
  • Next Time: Energy Harvesting
Why worry about power? Power Dissipation

Lead microprocessors power continues to increase

Power delivery and dissipation will be prohibitive

Source: Borkar, De Intel®
Why worry about power? Chip Power Density

- Hot Plate
- Nuclear Reactor
- Rocket Nozzle

...chips might become hot...

Source: Borkar, De Intel®
State-of-the-Art Processor Power

• Reported at ISSCC 2008
  – Sun Chip Multithreading SPARC: 65 nm CMOS, 2.3 GHz at 1.2 V, 250 W
  – Intel Quad Core Itanium: 65nm CMOS, 2.0 GHz, 170 W

• Careful design still keeping power below 100 W
  – Montecito ISSCC 2005 (dual-core Itanium): 300 W down to 100 W
Previous Processor Power

• Reported at ISSCC 2004
  – IBM POWER5: 130 nm SOI, 1.5 GHz at 1.3 V, incorporates 24 digital temperature sensors distributed over die for hot-spot throttling
  – Sun UltraSPARC: 130 nm CMOS, 1.2 GHz at 1.3 V, 23 W typical dissipation
  – IBM PowerPC 970: 130 nm SOI, 1.8 GHz at 1.45 V, 57 W typical dissipation
  – IBM PowerPC 970+: 90 nm SOI, 2.5 GHz at 1.3 V, 49 W typical dissipation
Intel D865GVHZ Motherboard Example

<table>
<thead>
<tr>
<th>Mode</th>
<th>DC Power</th>
<th>+3.3 V</th>
<th>+5 V</th>
<th>+12 V</th>
<th>-12 V</th>
<th>+5 VSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum loading</td>
<td>190.00 W</td>
<td>5.00 A</td>
<td>11.00 A</td>
<td>9.00 A</td>
<td>0.03 A</td>
<td>0.60 A</td>
</tr>
<tr>
<td>Maximum loading</td>
<td>286.00 W</td>
<td>11.00 A</td>
<td>15.00 A</td>
<td>13.00 A</td>
<td>0.10 A</td>
<td>1.40 A</td>
</tr>
</tbody>
</table>

- Minimum load assumes no applications running and no current draw from USB ports or PCI cards
- Maximum load assumes heavy gaming application and 500 mA drawn from each USB port, but no PCI add-in cards
- Specs for board power delivery system, not specific processor-memory configuration
- From Intel Desktop Board Technical Product Specification, Nov. 2003, p. 78
PC Power Supply Design

- **Multiple output voltages each with different current (power) specs**
  - Supports legacy chip i/o standards, displays, disk drives, speakers, peripherals, modems, etc.
  - Processor supply voltages generated independently of silver box (allows separate optimization, variable voltage design, supports last minute system configuration)

- **System power variable with workload**
  - 1.5X difference between minimum and maximum power
  - Variability impacts power electronics design (load regulation of output voltage)

- **Always minimize cost!**
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Power Sources for Portable Applications

• Portable electronics drives need for low weight, small volume, stored energy sources
  – Want high specific energy or energy per unit mass (Joules / kg)
  – Maximize energy density or energy per unit volume (Joules / cm³)
  – Must meet peak output power demands

• Several stored energy options
  – Electrochemical cells (batteries) with various chemistries
  – Fuel cells possible alternative
  – Power MEMS which also rely on storing energy chemically and then converting it to electricity
Why worry about power? Battery Size/Weight

Expected battery lifetime increase over the next 5 years: 30 to 40%

From Rabaey, 1995
Recent Battery Scaling and Future Trends

- Battery energy density increasing 8% per year, demand increasing 24% per year (the Economist, January 6, 2005)
Battery Basics

• **Battery consists of several electrochemical cells**
  – Can be arranged in series (increase output voltage) or parallel (increase output current) or combination
  – Each cell consists of two terminals (anode and cathode) separated by electrolyte
  – These constitute cell’s active materials

• **When cell connected to load, oxidation-reduction reaction occurs**
  – Electrons transferred from anode to cathode
  – Transfer converts chemical energy stored in active material to electrical energy
  – Flows as current through external load
Battery Discharge and Capacity Definitions

- As battery discharges, output voltage drops
  - Battery effectively disconnects from load once voltage drops below cutoff
- Battery capacity defined in charge units (A-h) instead of energy
  - *Full charge capacity*: capacity remaining at beginning of discharge cycle
  - *Full design capacity*: capacity for new battery
  - *Theoretical capacity*: maximum extractable charge based on amount of active material
  - *Standard capacity*: charge extracted under standard load and temperature conditions
  - *Actual capacity*: charge delivered under specific load and temperature conditions
Rate Dependent Capacity

• Battery capacity decreases as discharge rate increases
  – When fully charged, electrode surface has maximum concentration of active species
  – Under loading, active species consumed by reaction at electrode and replenished by diffusion from electrolyte bulk
  – Diffusion cannot keep pace with electrochemical reaction, so concentration gradient builds up in electrolyte
  – As load increases, active species concentration at electrode drops below threshold (corresponding to cutoff voltage) and reaction cannot be sustained, eliminating current flow
  – Eventually cell recovers (*charge recovery*) as diffusion flattens concentration gradient

• For sufficiently low discharge rates, operation remains close to ideal
Rate Dependent Capacity Operation

- Rao et al., Computer, Dec. 03
Lithium-Ion Rate Dependent Capacity

- Rao et al., Computer, Dec. 03

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Temperature Effect

• Like any chemical reaction, temperature strongly affects battery discharge behavior

• Below room temperature, cell chemical activity decreases
  – Cell internal resistance increases, reducing full charge capacity and increasing slope of discharge curve

• At high temperatures, internal resistance decreases
  – Full charge capacity and voltage increases
  – Higher rate of chemical activity (self-discharge) can offset these other effects and result in less actual capacity

• Difficult for designer to control temperature
Lithium-Ion Temperature Effect

- Rao et al., Computer, Dec. 03
Capacity Fading

- Lithium-ion popular choice for portables
  - High energy density and capacity

- Li-ion batteries lose fraction of capacity with each charge-discharge cycle
  - Unwanted side reactions (electrolyte decomposition, active material dissolution, passive film formation)
  - Irreversible side reactions increase internal cell resistance until battery fails
  - Limit effect by controlling depth of discharge before recharging (constrain battery to only shallow discharges leaving voltage relatively high for recharge)
  - Shallow discharge typically allows battery to undergo more cycles until cutoff voltage finally reached
Lithium-Ion Capacity Fading

- Rao et al., Computer, Dec. 03

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Battery Models

- **Physical models**
  - Most accurate, can be used to optimize battery design, but computationally intensive
  - Differential equations based on isothermal electrochemical model

- **Empirical models**
  - Peukert’s Law: \( C = LI^\alpha \)
  - \( C \) is capacity, \( L \) is lifetime, \( I \) is constant current
  - Ideal battery with constant current load yields \( \alpha = 1 \)
  - Exponent provides simple way to model rate dependence
  - Does not model time-varying loads
Battery Models (cont.)

• **Electrical circuit models**
  – Attempt to provide equivalent circuit model for battery
  – Model using linear passive elements, voltage sources, and lookup tables
  – Compatible with HSPICE, Verilog / VHDL

• **Add circuit complexity to capture all effects**
  – Model capacity fading with capacitor whose value decreases linearly with number of charge-discharge cycles
  – Temperature effect modeled as RC circuit with temperature-dependent voltage sources

• **Discrete-time (state) model in VHDL**
Battery Electrical Circuit Models

- Rao et al., Computer, Dec. 03
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Fuel Cell Alternative to Battery

• Nickel-cadmium and lithium-ion batteries increased energy capacity 10-15% per year historically
  – Estimate another 15-25% improvement in capacity

• Fuel cells and batteries both generate electricity through electrochemical reactions
  – Chemical reaction between oxygen and hydrogen or hydrogen-rich substance (e.g., methanol current focus of research)
  – Electrodes draw fuel toward porous membrane
  – Hydrogen-rich material breaks down, releasing hydrogen and electrons
  – Hydrogen reacts with oxygen to form water, electrons flow as current in external circuits
Fuel Cells for Portable Applications

- Users can add more fuel to continue operation
- Research on micro fuel cells focused on membrane
  - Proton-exchange membrane (PEM) traditional material but usually too large to be portable
  - Stacks of porous silicon wafers dramatically increases number of generated electrons (proportional to membrane surface area)
  - Other research ongoing on membranes (see reading)
- Still being investigated as a practical battery alternative
  - Challenges include standardization, cost, fuel flammability, market in billions of units?
  - May reach significant market in next 1-2 years
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Power MEMS Motivation

• Battery Technology Limits
  – Enormous military and commercial demand for something better
  – Metric: W-hr/kg
    • Current Battery Technology ~ 100-200 W-hr/kg

• High Density Energy Sources
  – Propulsion
  – Heat Generation
  – Refrigeration
    • Chip Cooling

• Schmidt, ISSCC 03
Power Generation MEMS Options

• Energy Scavenging/Harvesting
  – Vibration
  – Heel Strikes
  – Residual Heat

• Fuel Burning
  – ThermoElectric (TE)
  – ThermoPhotoVoltaic (TPV)
  – Fuel Cells
    • Requires Hydrogen Source
  – Rotating (moving) Machinery
    • Microturbines

• Schmidt, ISSCC 03
Batteries vs. Fuel

• Batteries
  – ~500 Watt-hours per kilogram for Primary
  – ~175 W-h/kg for Secondary (Rechargeable)

• Fuel Combustion
  – ~39,000 W-h/kg for Hydrogen
  – ~14,000 W-h/kg for Propane or Butane
  – ~12,000 W-h/kg for Gasoline
  – ~6,000 W-h/kg for Methanol

• The Challenge:
  – Efficient, Lightweight Conversion

• Schmidt, ISSCC 03

Courtesy: Franz, Schaevitz, Lilliputian Systems
Fuel Burning Advantages vs. Batteries

- Schmidt, ISSCC 03
Thermoelectric Generators

- Schneider, ISSCC 03

Passive Device
Fuel Insensitive
High Power Density
  - Well-Established Macro-Scale Technology

- Schmidt, ISSCC 03
Thermoelectric Generation Materials

- SiGe:
  - Readily Available Semiconductor
  - High Efficiency
  - High-Temperature Operation

- Schmidt, ISSCC 03
Membrane Based Thermoelectric Generator

- Schmidt, ISSCC 03

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Generator Operation

- Schmidt, ISSCC 03
Thermoelectric Generator Efficiency

- **Efficiency of thermoelectric generator inadequate**
  - High temperature region localized to membrane
  - Heat flow from membrane too high for efficient conversion
  - Overall device efficiency around 0.02% at 500 degrees Celsius
  - Biggest loss mechanism is thermal conduction in SiN membrane (without this loss, efficiency boosted to 0.4%)
  - Running hotter (between 700 and 900 degrees Celsius) raises efficiency to 10%, superior to batteries

- **Significant optimizations in metal contacts, reaction chamber design**

- **Higher power density option: micro gas turbine**
MIT Micro Gas Turbine Generator

- Schmidt, ISSCC 03

<table>
<thead>
<tr>
<th></th>
<th>Micro Turbo Generator</th>
<th>LiSO2 Battery (BA5590)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output</td>
<td>50 W</td>
<td>50 W</td>
</tr>
<tr>
<td>Weight</td>
<td>50 grams</td>
<td>1000 grams</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>3500 W-hr/kg</td>
<td>175 W-hr/kg</td>
</tr>
</tbody>
</table>
Hydrogen Micro Turbine Demonstration

Thrust = 11 g
Fuel burn = 16 g/hr
Engine weight = 2 grams

Turbine inlet temp = 1600°K (2421°F)
Rotor speed = 1.2 x 10^6 RPM
Exhaust gas temp = 970°C

- Schmidt, ISSCC 03
Micro Turbine Technical Challenges

• High speed rotation (greater than 1 Million RPM)
  – Constrains fabrication precision

• Combustion using silicon package (instead of SiC)
  – Constrains conversion efficiency and packaging

• Electrical conversion nontrivial
  – Electrostatic induction (traditionally used electromagnetic induction) and new materials
  – Power electronics for conversion including inductors

• Manufacturing flow complexity (6 wafers, 25 masks)
  – Controlling etches

• Schmidt, ISSCC 03
Micro Rotary Engine

MEMS Implementation

- Wikipedia, GFDL 05
- UCB BSAC, 05

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- Review: Adiabatic Charging and Energy Recovery
- Lecture 9: Dynamic Energy Recovery Logic
- Lecture 9: Power and Clock Waveform Generation
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- Next Time: Energy Harvesting
Announcements

• Design Project 2 due Monday, March 3, at 5 PM in instructor’s office

• Final project proposals also due Monday
  – Email a brief description (1 paragraph) of what you plan to evaluate for the final project
  – Attach a paper or papers from the literature that describes the circuit/technology/etc. which is the focus of the project
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Adiabatic Charging Analysis

\[ \Phi(t) = \int R C \left( \frac{dV_c}{dt} \right) + V_c \]

- Solve differential equation assuming input is voltage ramp with duration T
Energy Dissipated With Ramp Driver

\[ E_{diss} = \int_0^\infty i_R(t)V_R(t)\,dt = \int_0^\infty \frac{(\Phi - V_c(t))^2}{R} \,dt \]

\[ = \int_0^T \frac{(\Phi - V_c(t))^2}{R} \,dt + \int_T^\infty \frac{(\Phi - V_c(t))^2}{R} \,dt \]

\[ = \frac{RC}{T} CV_{DD}^2 \left[ 1 - \frac{RC}{T} + \frac{RC}{T} e^{-T/RC} \right] \]

- Consider the extreme cases of \( RC \) with respect to \( T \)
  - \( RC << T \) implies less energy dissipation
Example Voltage Ramp: Stepwise Charging

\[ V_{out} \]

\[ \Phi_{N-1} \]

\[ V_{N-1} \]

\[ C_T \]

\[ V_1 \]

\[ \Phi_1 \]

\[ \Phi_0 \]

\[ C_T \]

\[ V_0 \]

\[ \Phi_{GND} \]

\[ \Phi_N \]

\[ \text{Out} \]
Next Stage Controlled Energy Recovery

\[ \Phi_0 \]

\[ F_0 \]

\[ \overline{P}_0 \]

\[ x \]

\[ y_0 \]

\[ P_0 \]

\[ \Phi_1 \]

\[ F_1 \]

\[ F_1^{-1} \]

\[ \overline{P}_1 \]

\[ y_1 \]

\[ P_1 \]
Cascaded Logic Energy Recovery Timing

- Charge \( n \)th stage nodes and then discharge \((n-1)\)th stage nodes
- How do we implement the energy recovery phase?
Energy Recovery System Block Diagram

- Use circuits to generate power / clock waveforms
- Generators must use as little power as possible
  - Resonant RLC circuits often used in these applications
  - Minimize parasitic losses in power / clock generator
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