Outline

• Announcements

• Review: Heat Transfer, Thermal Circuits, Thermal Design Issues
Review: Heat Transfer Mechanisms

• Conduction
  – Transfer medium is stationary
  – Heat transfers through vibratory motion of atoms, molecules
  – Ex: heat sink, thermoelectric generators

• Convection
  – Transfer occurs through mass movement – fluid flow (liquid or gas)
  – Natural: buoyancy created by temperature gradients causes fluid movement
  – Forced: mass flow created by pumps or fans
  – Ex: most computers use forced convection air cooling
Review: Thermal Resistance

• Rate $Q_{12}$ at which heat energy is transferred from body at temperature $T_1$ to temperature $T_2$ is linear proportional to temperature difference:

$$Q_{12} = \frac{T_1 - T_2}{R_\Theta}$$

• Define a thermal resistance $R_\Theta$ between bodies

• Analogous to Ohm’s Law: $Q_{12}$ corresponds to current $I$; $T_1$, $T_2$ corresponds to voltage $V_1$, $V_2$; $R_\Theta$ corresponds to resistance $R$
Mass at temperature $T_1$ (thermal capacitance), being supplied heat $Q$, in contact with sink at temperature $T_S$

Final (steady-state) temperature: $T_1 = R_{\Theta}Q + T_S$
Laser Thermoreflectance Measurement

- **Thermoreflectance**: variation of the reflection coefficient of a material with temperature
- Using laser beam as light source and sensing reflected light with a photodiode, variation of diode current can be related to temperature change in illuminated area:
  \[
  \Delta T = \psi^{-1} \frac{\Delta I}{I}
  \]
- Exact value of \(\psi\) depends on material (1.35 \(\times\) 10^{-4} K^{-1} for pure Si)
- Fast surface thermometer (dc to 10 MHz) with 1 \(\mu\)m spatial resolution large dynamic range (\(\Delta T=10^{-3}\) to \(10^2\) K)
Heat Transfer On-Die Experiment

- Heat source integrated on chip
- Area with no metal, constant $\psi$ since homogeneous thickness of passivation and oxide layers

Altet, JSSC 2001
Thermoreflectance Experiment Results

- Heat source activated at 23 mW for 100 μs
- ΔT plotted along x-axis defined above
- Temperature wave diffuses as if along RC ladder

Altet, JSSC 2001
Theory Agreement with Experiment Results

- Temperature wave amplitude as function of distance, for different heat source frequencies
- Calculated using diffusion equation (\(RC\) network limit)

Altet, JSSC 2001
Review: Typical Microprocessor Package

- Heat spreader expands thermal interface between die and heat sink plate (die back side)
- Thermal conduction through flip-chip bumps and package solder balls into PCB (another heat sink) on die front side
- Two paths with thermal resistances in parallel, back side of die path more efficient

Gurrum, 2004
Principles of Temperature Measurement

- Bipolar devices can be used for temperature sensing in CMOS technology
  - Lateral BJT: current flow parallel to substrate
  - Substrate BJT: current flow into substrate
  - Substrate devices have more ideal behavior, less sensitive to mechanical stress

- In typical n-well CMOS process, form substrate pnp transistor by p⁺ source/drain diffusion in n-well
  - Collector formed by substrate

- Main disadvantages: substrate usually grounded, low current gain (around 10)
  - OK for temperature sensing applications
Substrate PNP Transistor

- Disadvantages can be relieved by BiCMOS process with explicit bipolar devices

R. Amirtharajah, EEC216 Winter 2009

Pertijs, 2004
Temperature Measurement Approach

- Use BJT base-emitter voltage ($V_{BE}$) as temperature measurement
- Transistor biased in forward-active has exponential dependence of collector current $I_C$ on $V_{BE}$:

$$I_C(T) = I_S(T) \exp \left( \frac{q V_{BE}}{kT} \right)$$

- $k$ is Boltzmann’s constant, $q$ the electron charge, and $I_S$ the transistor saturation current
**$I_S$ Temperature Dependence**

\[
I_C(T) = A_E C T^n \exp \left( \frac{q(V_{BE} - V_{g0})}{kT} \right)
\]

- $A_E$: emitter area
- $C$ and $\eta$: process-dependent constants
- $V_{g0}$: bandgap voltage extrapolated to 0 K
Base-Emitter Voltage vs. Collector Current

\[ V_{BE}(T) = V_{g0} \left( 1 - \frac{T}{T_r} \right) + \frac{T}{T_r} V_{BE}(T_r) \]
\[ - \frac{kT}{q} \ln \left( \frac{T}{T_r} \right) + \frac{kT}{q} \ln \left( \frac{I_C(T)}{I_C(T_r)} \right) \]

- \( T_r \) and \( V_{BE}(T_r) \) are a reference temperature and the base-emitter voltage at that temperature:

\[ V_{BE}(T_r) = V_{g0} + \frac{kT_r}{q} \ln \left( \frac{I_C(T_r)}{A_E C T_r^\eta} \right) \]
Temperature Dependence of $V_{BE}$

- Almost linear dependence with sensitivity about -2 mV/K
- Curvature nonlinearity can be compensated (see bandgap reference circuits)

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Pertijs, 2004
Sensitivity Variation Due to Process

• Since $V_{BE}(T_r)$ process dependent, sensitivity also process dependent

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Pertijs, 2004
ΔV_{BE} Temperature Measurement

• Eliminate process dependence by using differential measurement

• Measure ΔV_{BE} between base-emitter voltages of a transistor operated at two current densities I_{C1} and I_{C2}:

\[ \Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln \left( \frac{I_{C2}}{I_{C1}} \right) \]

• For constant collector current ratio, ΔV_{BE} is PTAT
$\Delta V_{BE}$ Measurement Circuits

- Single diode-connected substrate pnp with switched current sources with ratio $p$
- Two diode-connected substrate pnp’s with current ratio $p$ and emitter area ratio $r$

Pertijs, 2004
Measurement Nonidealities

• Proper matching required to ensure accuracy
  – E.g., ratio of emitter areas set by parallel combination of identical unit transistors

• Typical value of $pr$ ratio is 10
  – Results in sensitivity of $\Delta V_{BE}$ around 200 $\mu$V/K
  – Small sensitivity requires offset-cancellation in readout circuitry, A/D converter

• Assuming good matching, accuracy then limited by pnp transistor nonidealities
  – Ex: Series resistance, current-gain variation, high-level injection, Early effect (base width modulation)
  – Look at series resistance example
Substrate PNP With Parasitic Resistances

- Voltage drop across base and emitter resistances is added to $V_{BE}$ measured externally
- Results in an offset to PTAT temperature dependence of $V_{BE}$

Pertijs, 2004
ΔV_{BE} With Series Resistance

\[
\Delta V_{BE} = (I_{B1} - I_{B2})R_S + \frac{kT}{q} \ln\left(\frac{I_{C2}}{I_{C1}}\right)
\]

• Series resistance \( R_S = R_B + R_E(\beta_F + 1) \), where \( \beta_F \) is the transistor current gain in forward active regime

• For typical values, this results in a temperature offset of about 0.64 °C

• Offset can be eliminated by measuring \( V_{BE} \) at three transistor bias currents
$\Delta V_{BE}$ With Three Bias Currents

\[
\Delta V_{BE12} = (I_{B1} - I_{B2})R_S + \frac{kT}{q} \ln\left(\frac{I_{C2}}{I_{C1}}\right)
\]

\[
\Delta V_{BE32} = (I_{B3} - I_{B2})R_S + \frac{kT}{q} \ln\left(\frac{I_{C3}}{I_{C2}}\right)
\]

- Two equations in two unknowns can be solved for $R_S$ and $T$
- Must ensure matching among three biases
BiCMOS Differential Temperature Sensor

• Two examples use explicit NPN devices in BiCMOS process
• Better current gain and freedom of collector bias

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Alltet, JSSC 2001
• Temperature affects ring oscillator frequency and final counter value when enabled for fixed duration
• Implemented on FPGA to find hot spots
• Frequency varies slowly with temperature, must ensure counter difference is detectable

Lopez-Buedo, 2002
Conclusions

• **Temperature measurement important for system power management**
  – Monitor local heating to control clock gating, power supply voltage scaling
  – Helps reliability as well as power reduction

• **Analog circuits rely on temperature dependence of bipolar base-emitter voltages at constant current**
  – Highly accurate measurements even with poor bipolar performance (e.g., substrate pnp transistors in CMOS)
  – Use many analog compensation techniques to improve accuracy, eliminate transistor nonidealities

• **Digital circuits also possible but limited in accuracy**