EEC 216 Lecture #15: Temperature Measurement Circuits

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Outline

- **Announcements**
- **Review: Heat Transfer, Thermal Circuits, Thermal Design Issues**

Review: Heat Transfer Mechanisms

- **Conduction**
  - Transfer medium is <u>stationary</u>
  - Heat transfers through vibratory motion of atoms, molecules
  - Ex: heat sink, thermoelectric generators
- **Convection**
  - Transfer occurs through mass movement – fluid flow (liquid or gas)
  - <u>Natural</u>: buoyancy created by temperature gradients causes fluid movement
  - <u>Forced</u>: mass flow created by pumps or fans
  - Ex: most computers use forced convection air cooling

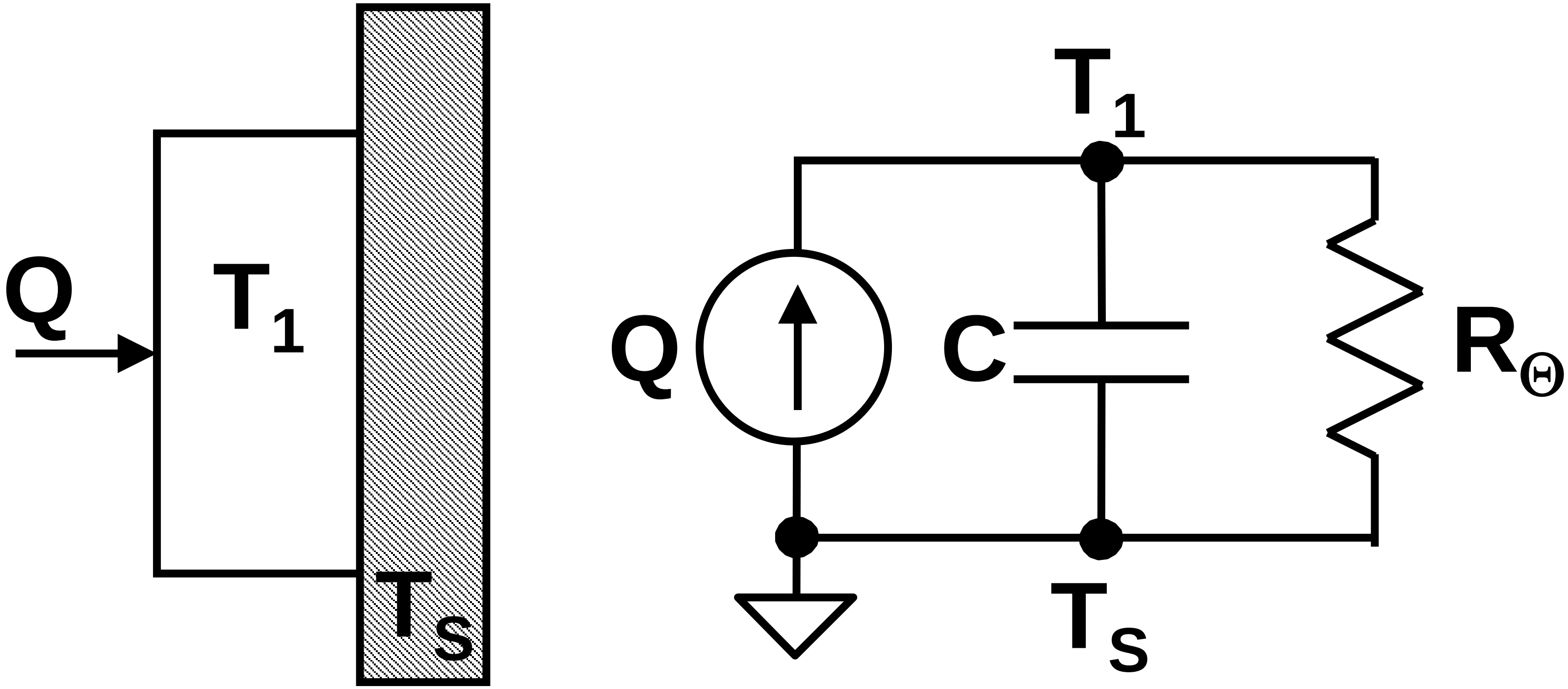
Review: Thermal Resistance

- **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 <u>thermal resistance</u> R_Θ 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_Θ corresponds to resistance *R***

Review: Thermal Circuit Example



- **Mass at temperature T_1 (thermal capacitance), being supplied heat Q, in contact with sink at temperature T_S**
- **Final (steady-state) temperature: $T_1 = R_\Theta Q + T_S$**

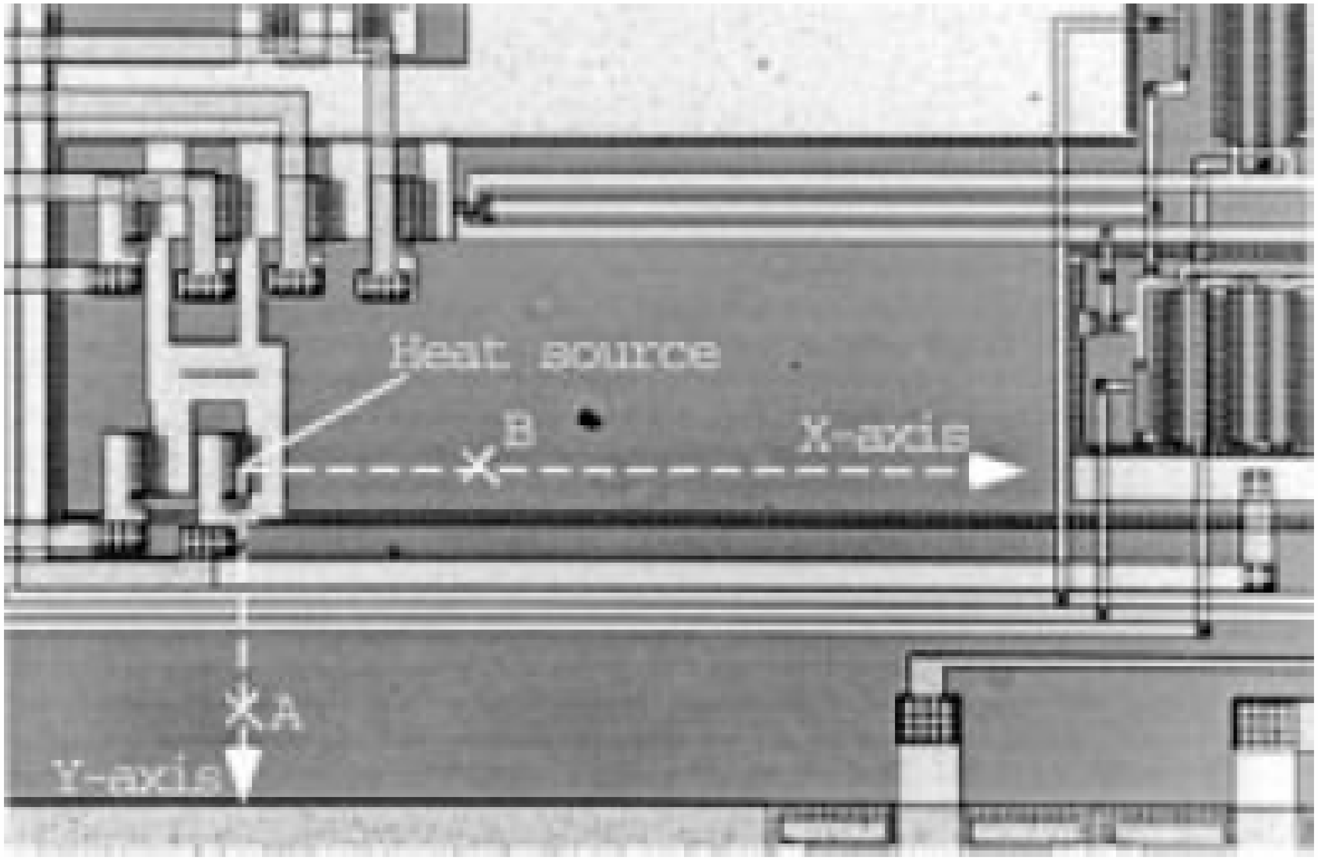
Laser Thermoreflectance Measurement

- **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 ψ depends on material (1.35 x 10^{-4} K^{-1} for pure Si)**
- **Fast surface thermometer (dc to 10 MHz) with 1 μm spatial resolution large dynamic range ($\Delta T = 10^{-3}$ to 10^{2} K)**

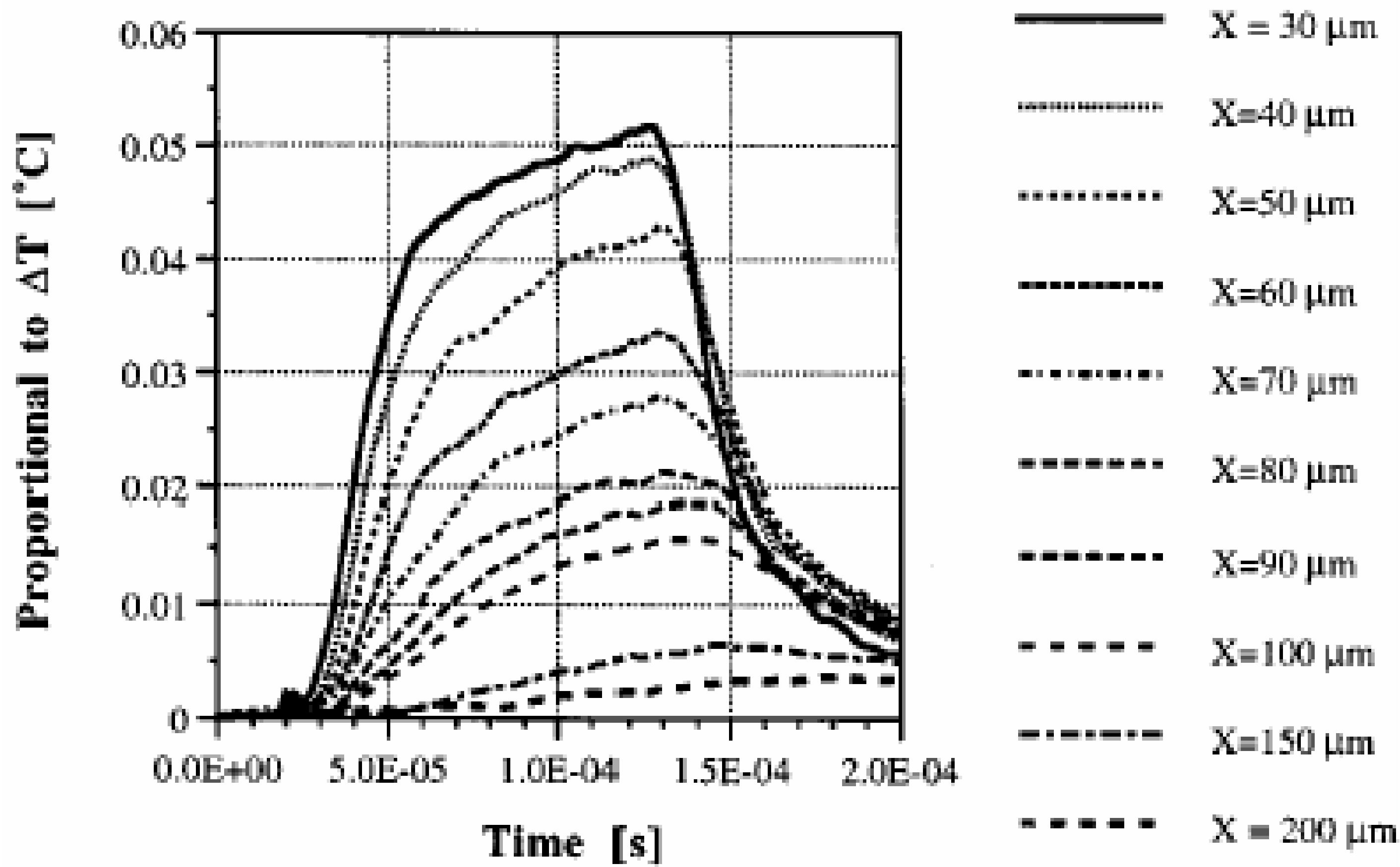
Heat Transfer On-Die Experiment



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

Altet, JSSC 2001

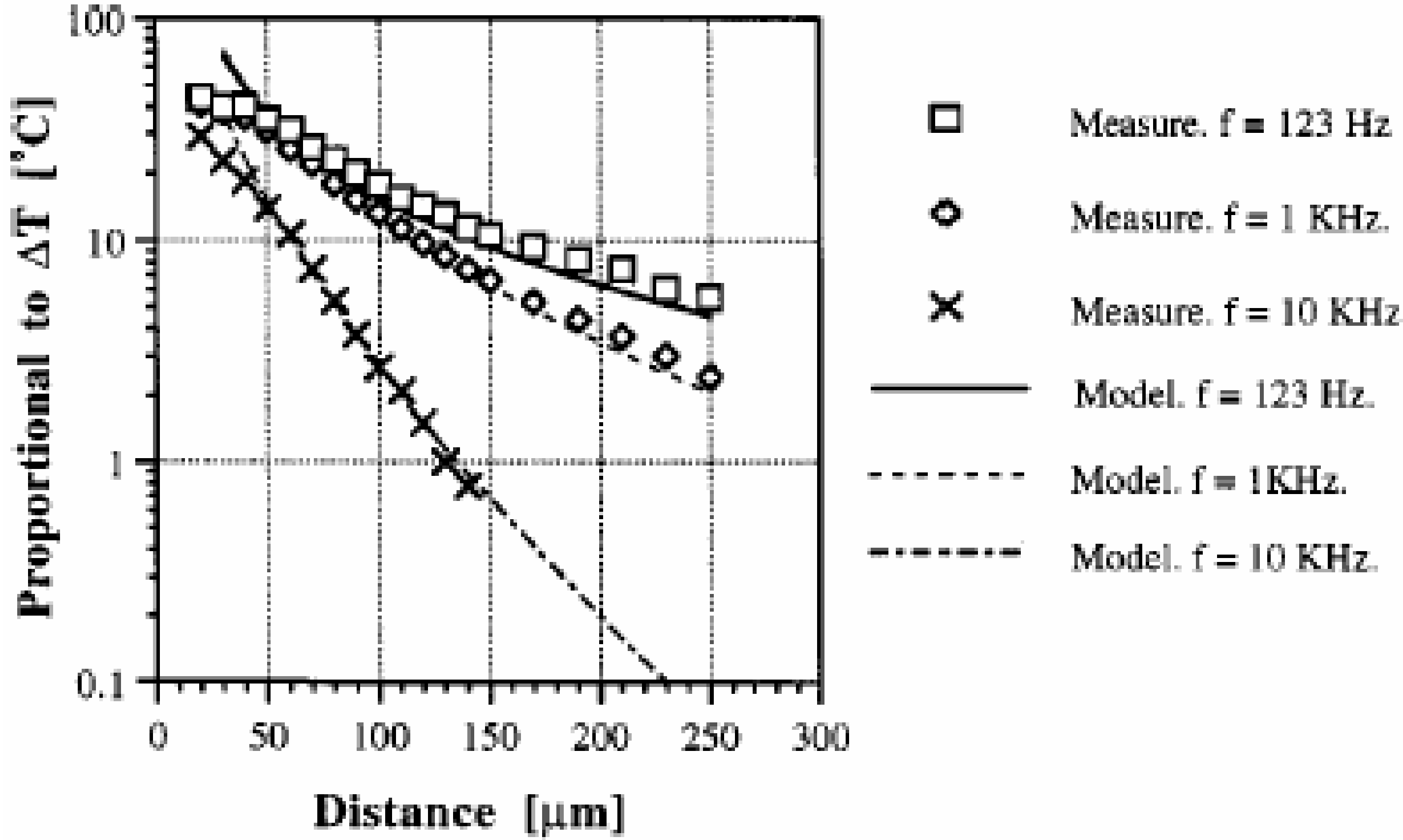
Thermoreflectance Experiment Results



- **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

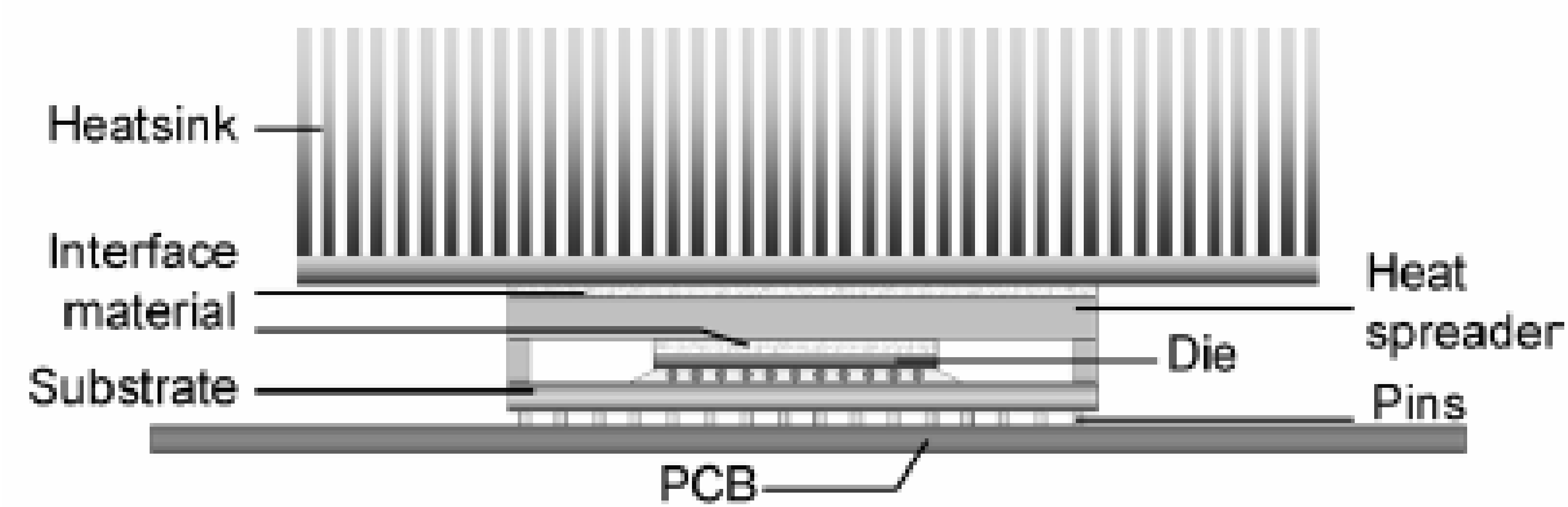
Theory Agreement with Experiment Results



- **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



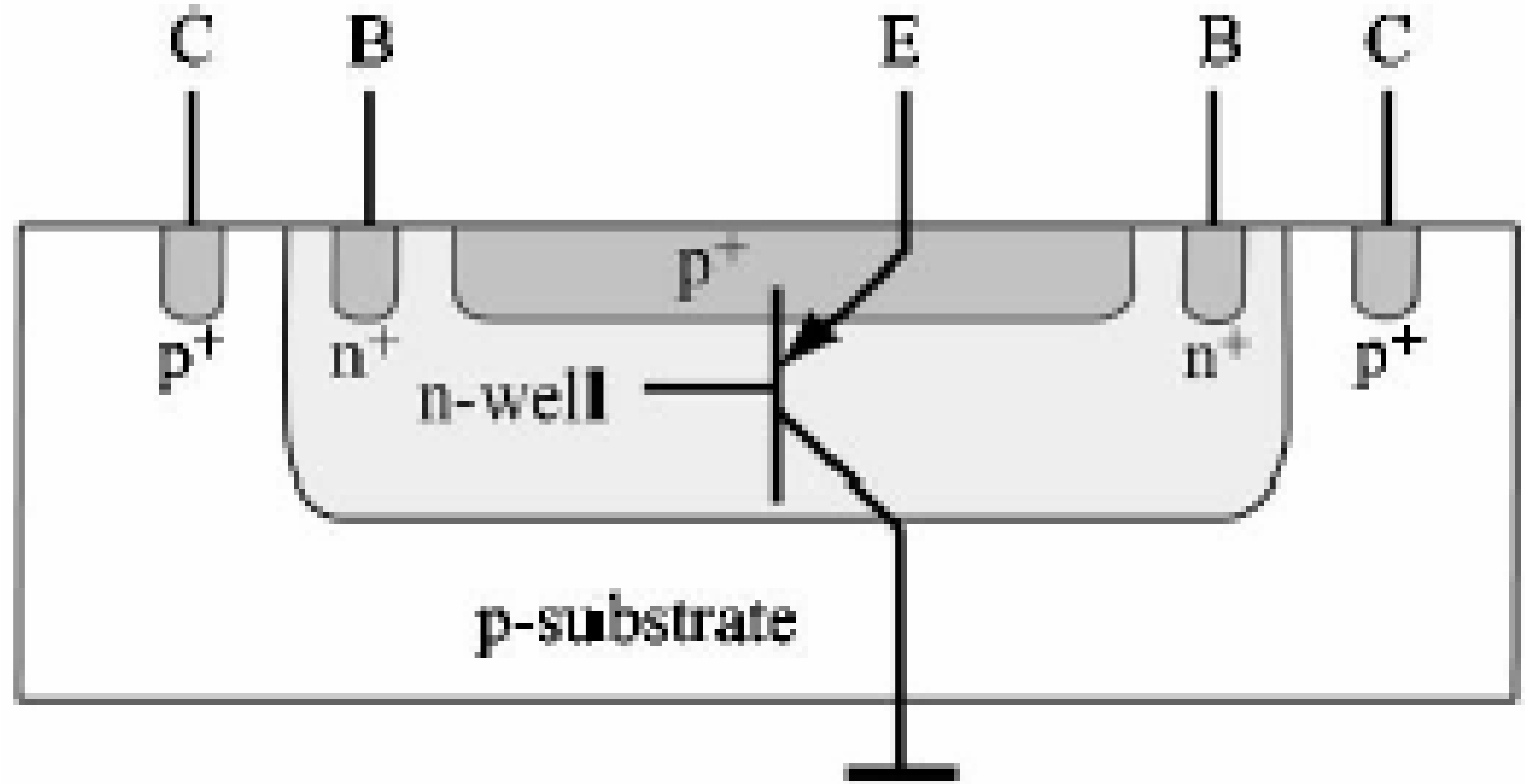
- **Heat spreader expands thermal interface between die and heat sink plate (die back side)**
- **Thermal conduction through flip-chip bumps and package solder balls into PCB (another heat sink) on die front side**
- **Two paths with thermal resistances in parallel, back side of die path more efficient**

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**

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}*:**

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

- ***k* is Boltzmann's constant, *q* the electron charge, and *I_S* the transistor saturation current**

I_S Temperature Dependence

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

- ***A_E*: emitter area**
- ***C* and η: process-dependent constants**
- ***V_{g0}*: bandgap voltage extrapolated to 0 K**

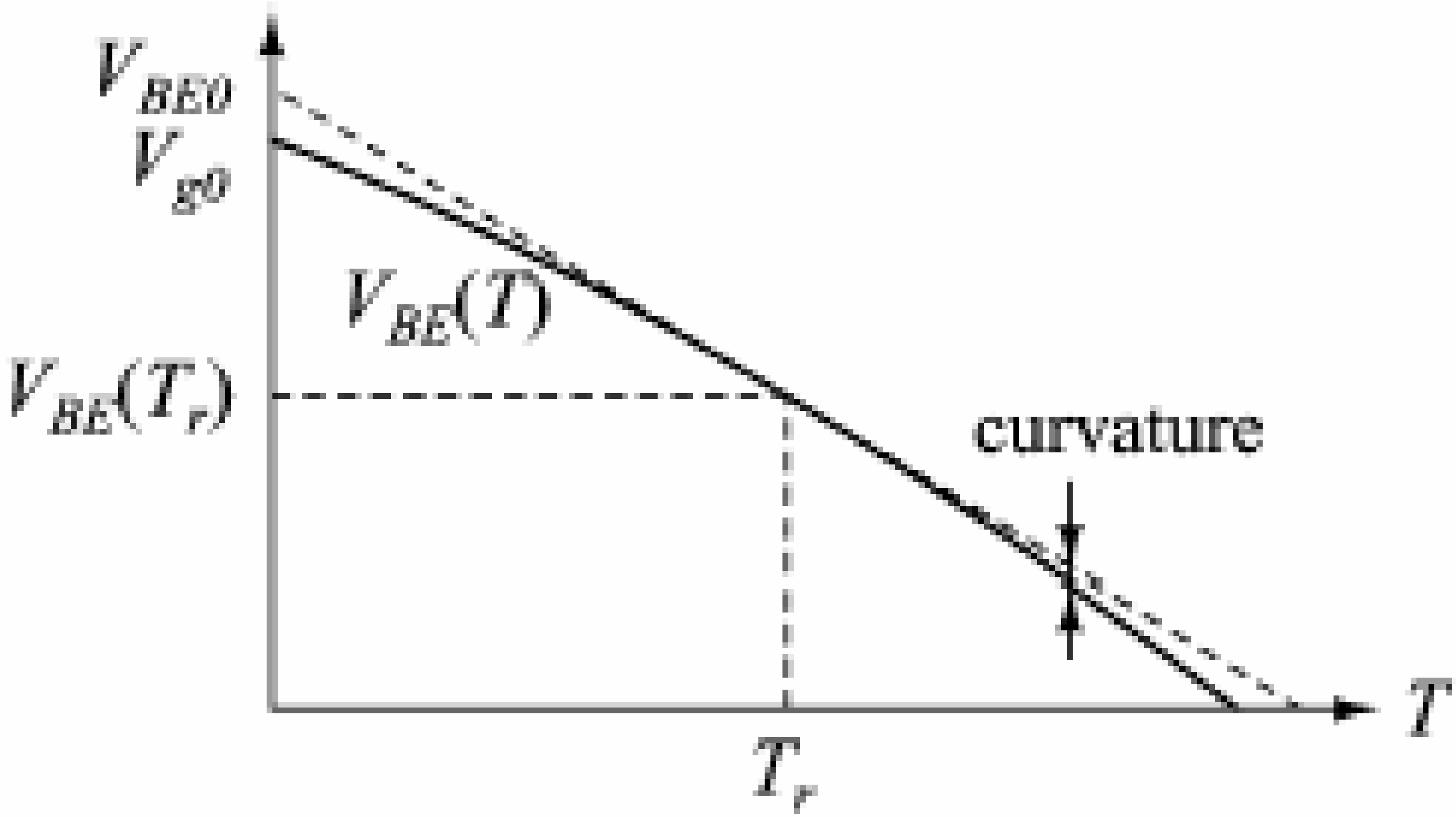
Base-Emitter Voltage vs. Collector Current

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

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

$$V_{\mathrm{BE}}(T_r) = V_{g0} + \frac{kT_r}{q}\ln\left(\frac{I_C(T_r)}{A_E C T_r^{\eta}}\right)$$

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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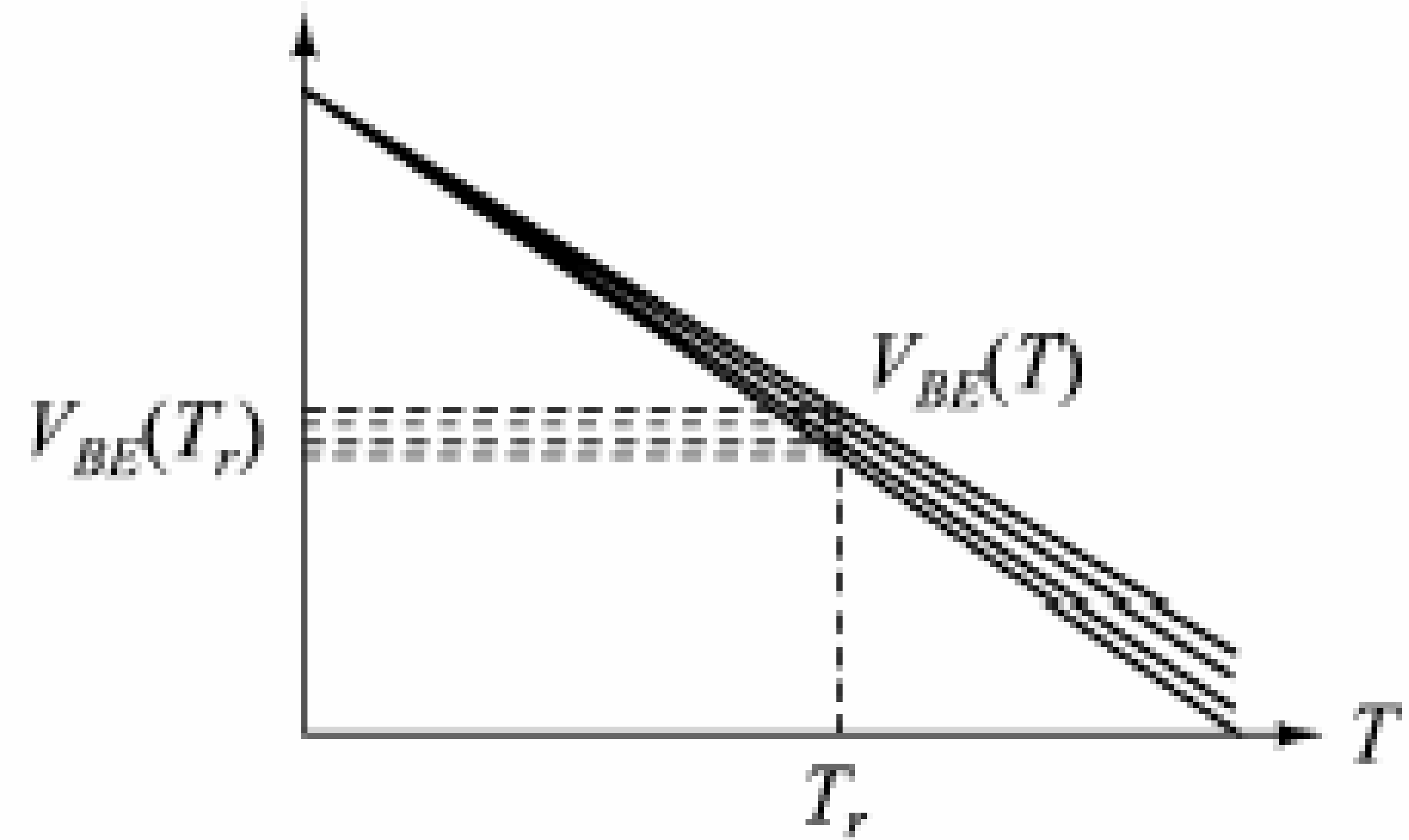
Sensitivity Variation Due to Process



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

Pertijs, 2004

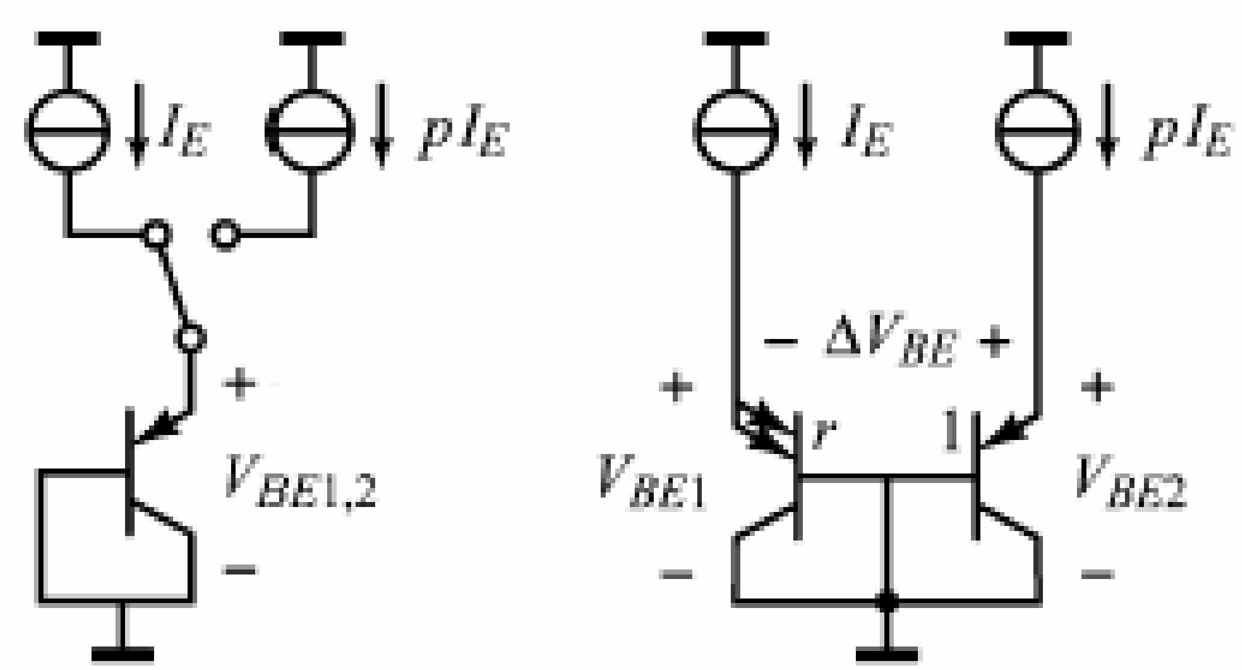
ΔV_{BE} Temperature Measurement

- **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**

ΔV_{BE} Measurement Circuits



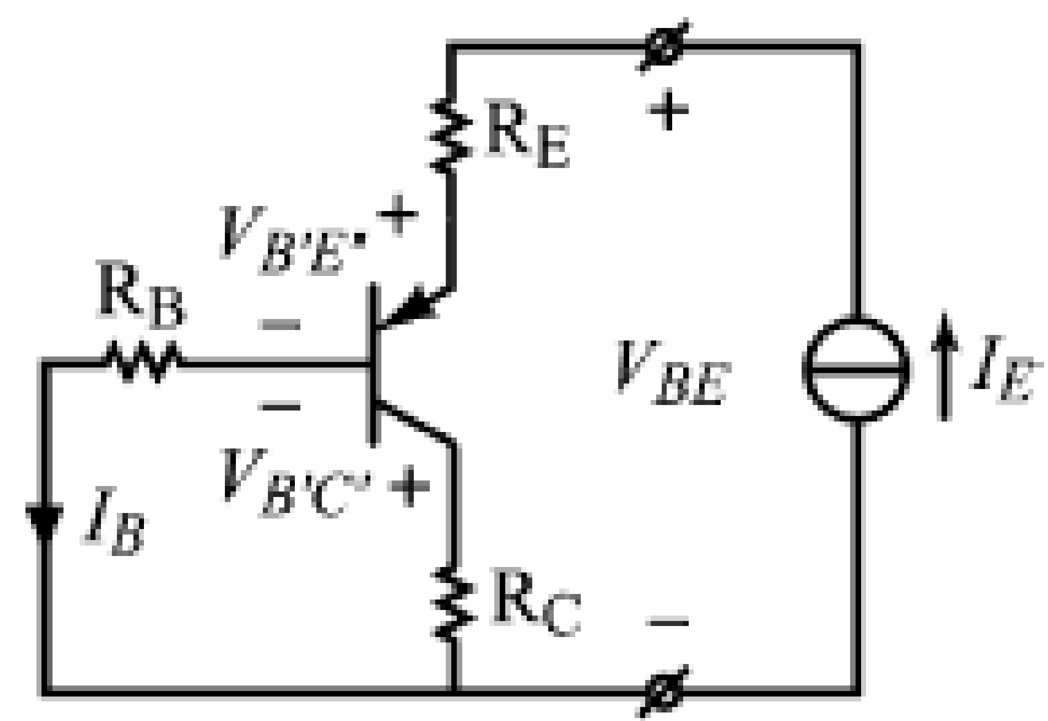
- **Single diode-connected substrate pnp with switched current sources with ratio *p***
- **Two diode-connected substrate pnp's with current ratio *p* and emitter area ratio *r***

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 ΔV_{BE} around 200 μV/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

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

- **Series resistance $R_S=R_B+R_E(\beta_F+1)$, where β_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 <u>three</u> transistor bias currents**

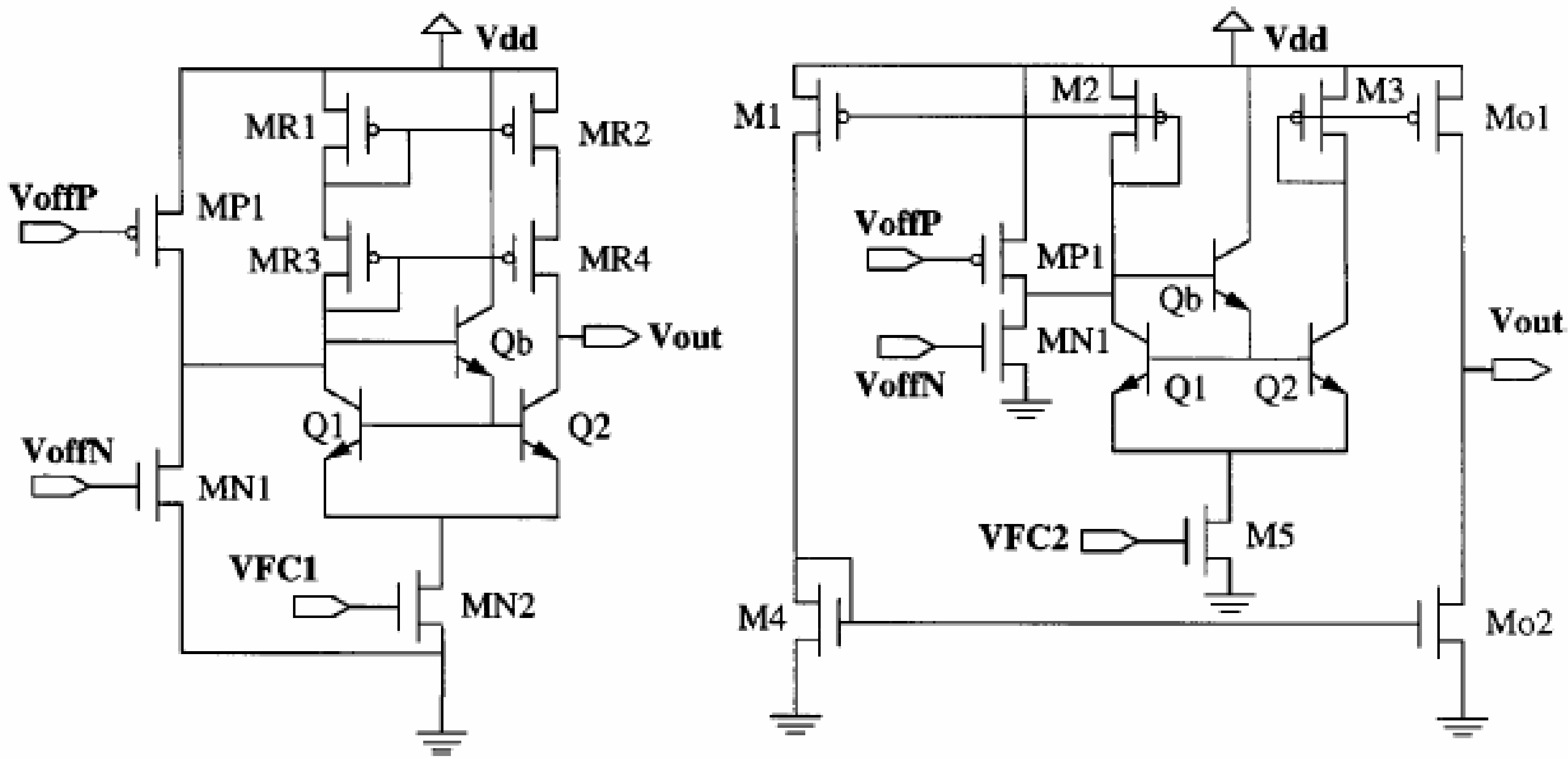
ΔV_{BE} With Three Bias Currents

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

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

- **Two equations in two unknowns can be solved for R_S and T**
- **Must ensure matching among three biases**

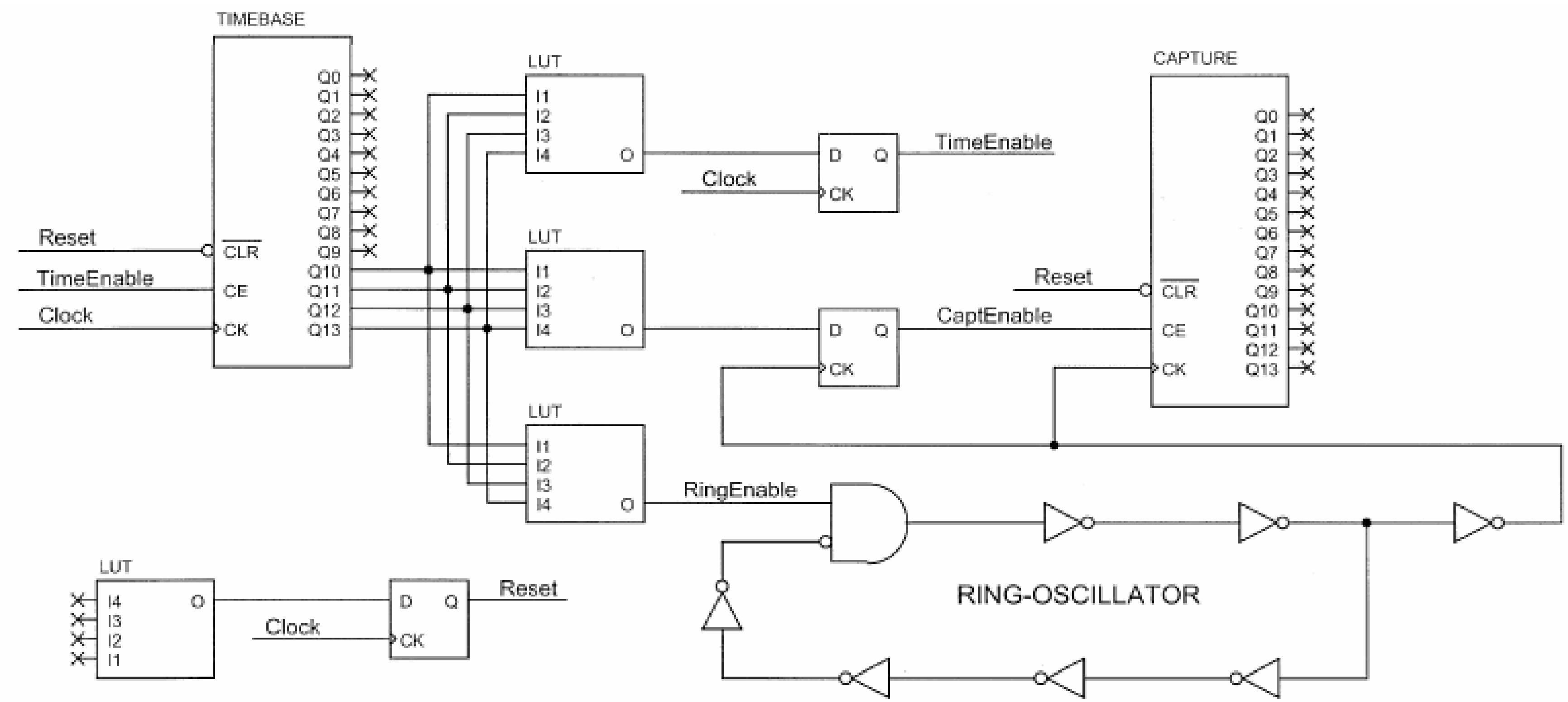
BiCMOS Differential Temperature Sensor



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

Alltet, JSSC 2001

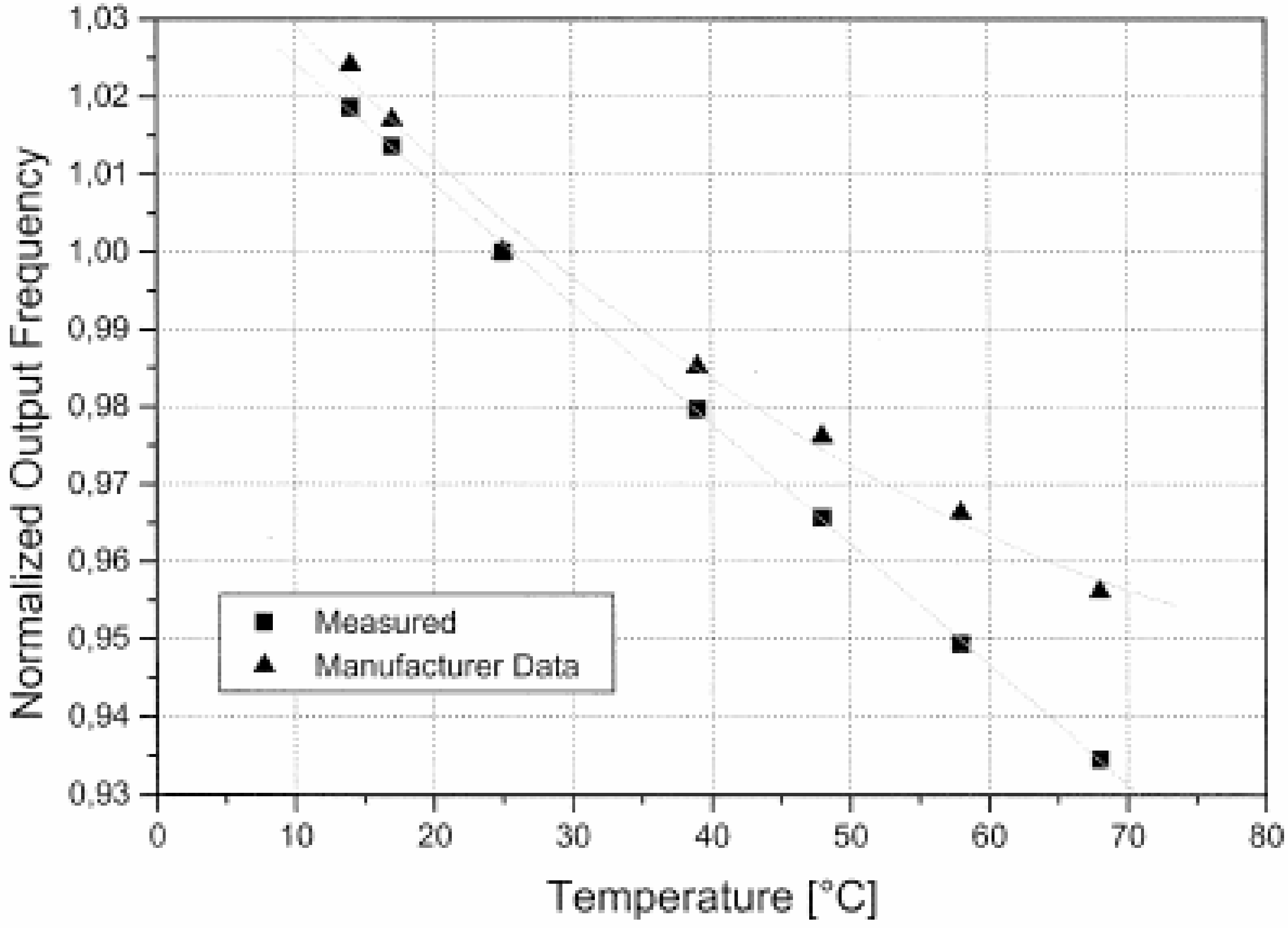
Digital Temperature Measurement Circuit



- **Temperature affects ring oscillator frequency and final counter value when enabled for fixed duration**
- **Implemented on FPGA to find hot spots**

Lopez-Buedo, 2002

Frequency vs. Temperature Dependence



- **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**