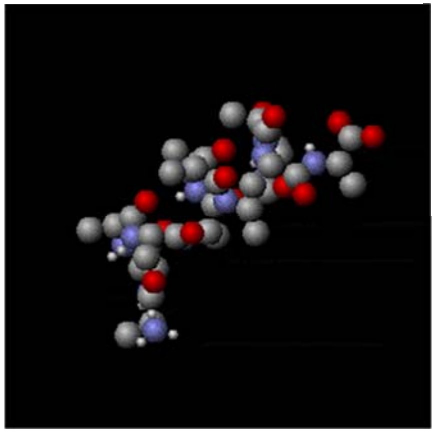
# 8. Body Temperature

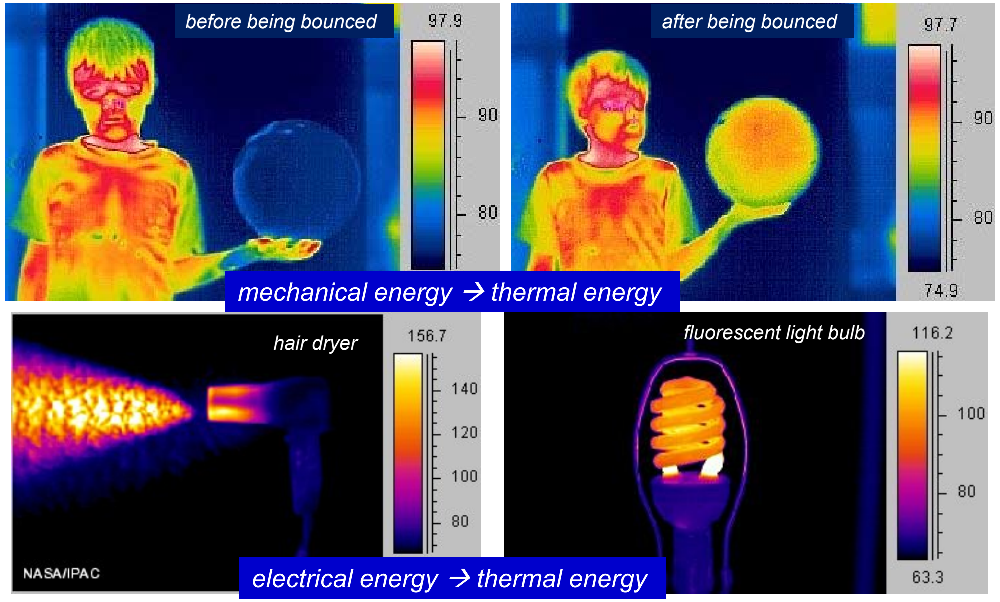
***Heat***: *the total energy of molecular motion in a substance.*
***Temperature***: *a measure of the average energy of molecular motion in a substance.*

- Body Temperature
- Measurement methods
  - Mercury thermometer
  - Electronic thermometer
  - Infrared thermometer
  - Zero-heat-flow
  - Dual-heat-flux



http://en.wikipedia.org/wiki/File:Thermally_Agitated_Molecule.gif

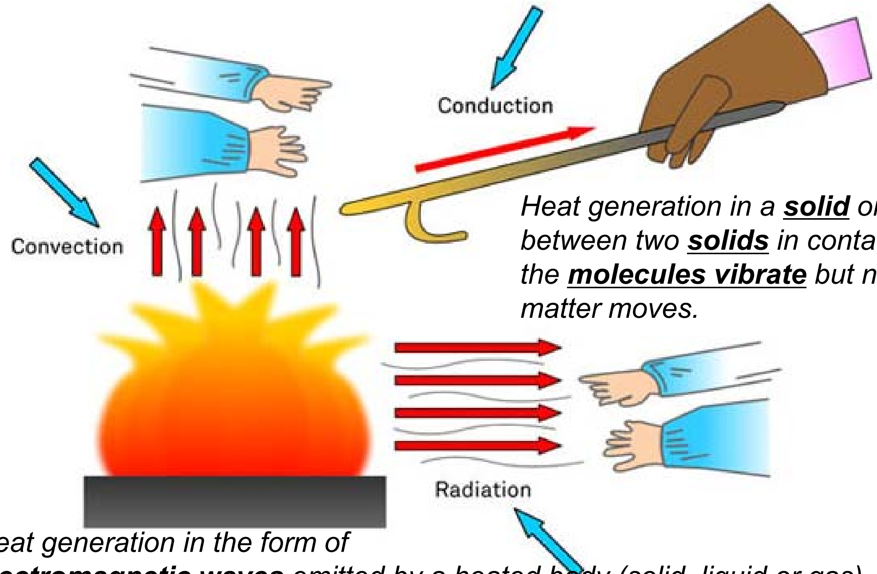
# Thermal Infrared Images






# Heat Transfer

*Heat generation in a **fluid** (liquid or gas) that is caused by a variation in temperature resulting from the **movement of molecules**.*



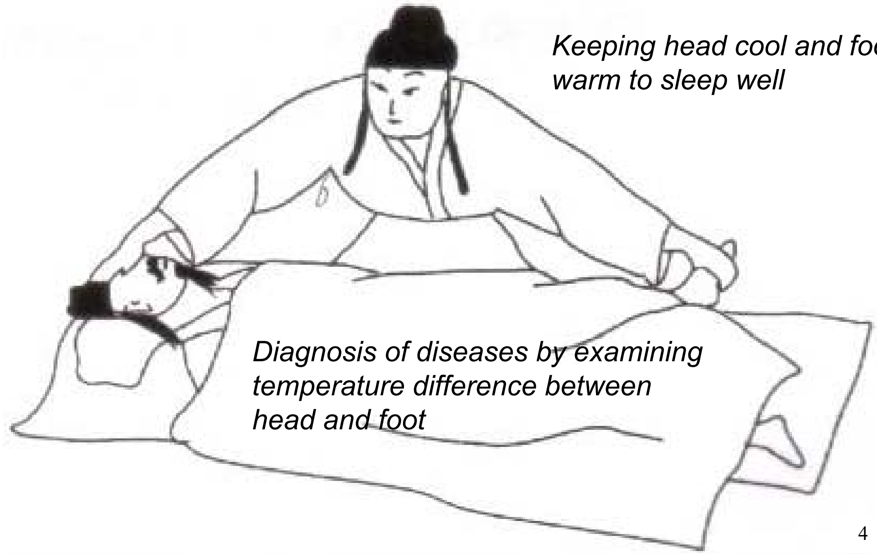

*Heat generation in a **solid** or between two **solids** in contact; the **molecules vibrate** but no matter moves.*

*Heat generation in the form of **electromagnetic waves** emitted by a heated body (solid, liquid or gas).*



# Archaic Method

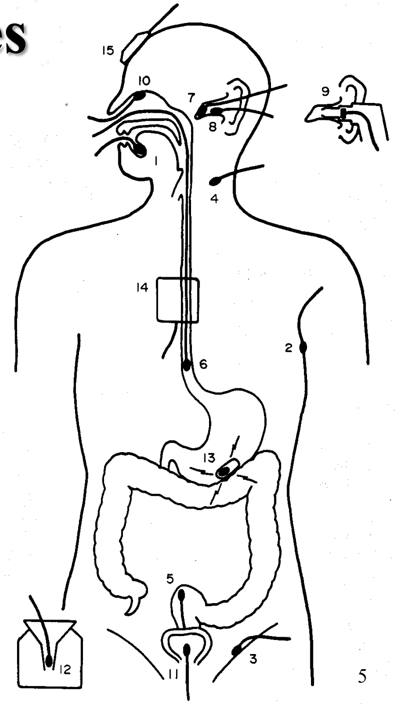
*Keeping head cool and foot warm to sleep well*



*Diagnosis of diseases by examining temperature difference between head and foot*

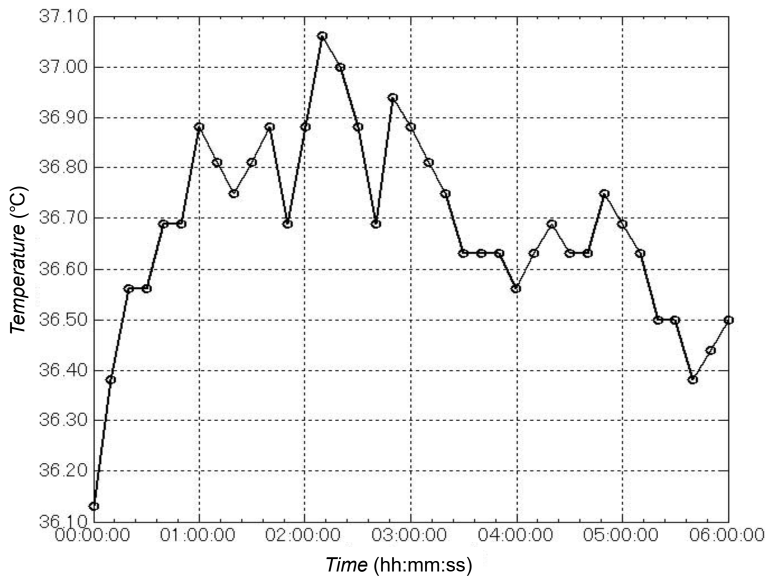
# Measurement Sites

1. *Sublingual space*
2. *Axilla*
3. *Groin*
4. *Neck*
5. *Rectum*
6. *Esophagus*
7. *Tympanum*
8. *External auditory canal*
9. *Tympanum by non-contact thermometer*
10. *Nasal cavity*
11. *Bladder*
12. *Urine*
13. *Digestive tract by radio capsule*
14. *Thorax by zero-heat-flow thermometer*
15. *Forehead by zero-heat-flow thermometer*





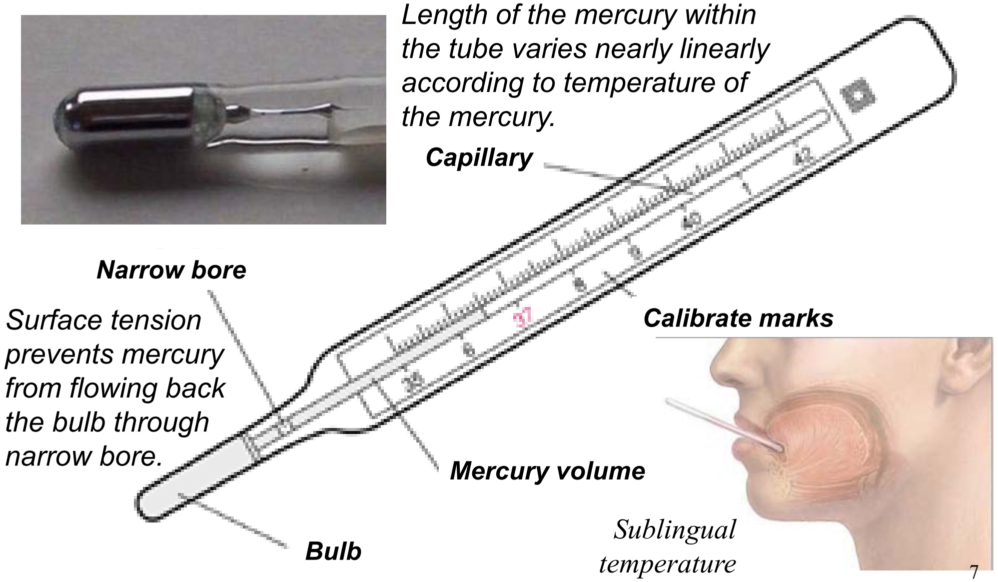

# Body Temperature during Sleep






# Mercury Thermometer

*German physicist Daniel Gabriel Fahrenheit in 1724*




*Sublingual temperature*

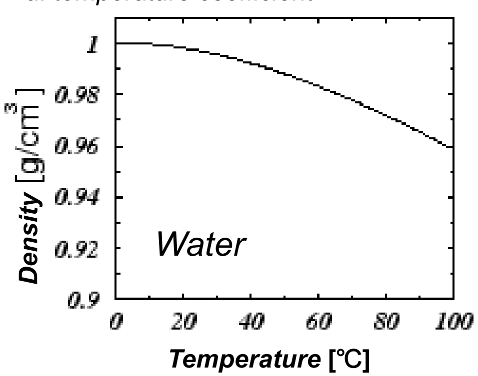


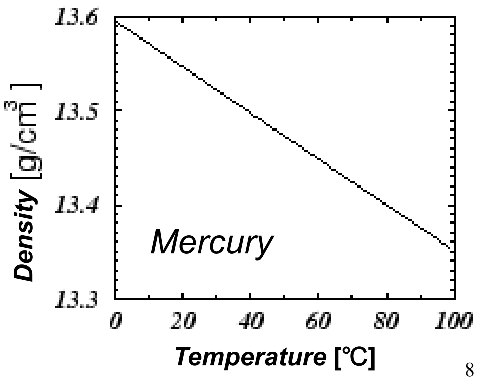
# Thermal Dilatability

*When mercury gets warmer it expands.*
*This increase in volume is measured by the scale on a mercury thermometer.*

$$\alpha(T,p) = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p \qquad \frac{\Delta V}{V} = -\frac{\Delta \rho}{\rho} \qquad \alpha(T,p) = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

*α: temperature coefficient*



# Thermoresistive Elements

*Temperature coefficient*: $\alpha = \dfrac{1}{R}\dfrac{dR}{dT}$

*band gap energy of the semiconductor*

*Resistivity*: $\rho \propto \exp\left(\dfrac{E_g}{2kT}\right)$

*Boltzmann constant*

*A thermistor has relatively higher resolution and larger temperature coefficient, typically about -0.04/K*

| *Material* | *Temp. Coeff.* ($K^{-1}$) | *Resistivity* ($\Omega$m) |
|---|---|---|
| *Platinum* | $3.9 \times 10^{-3}$ | $10 \times 10^{-8}$ |
| *Nickel* | $6.7 \times 10^{-3}$ | $6.8 \times 10^{-8}$ |
| *Aluminum* | $4.2 \times 10^{-3}$ | $2.7 \times 10^{-8}$ |
| *Tungsten* | $5.3 \times 10^{-3}$ | $5.5 \times 10^{-8}$ |



# NTC and PTC Thermistors

- Thermally sensitive resistor
  - Electrical resistance is sensitive to temperature change
  - Metal oxide such as iron, nickel, cobalt, manganese, copper, 2～4 mixture, molded into various shapes at 1200～1500°C
- Measurement range＝-50～350°C
- NTC（Negative Temperature Coefficient）
  - Inverse proportional relation between temperature change and resistance change
- PTC（Positive Temperature Coefficient）
  - proportional relation between temperature change and resistance change



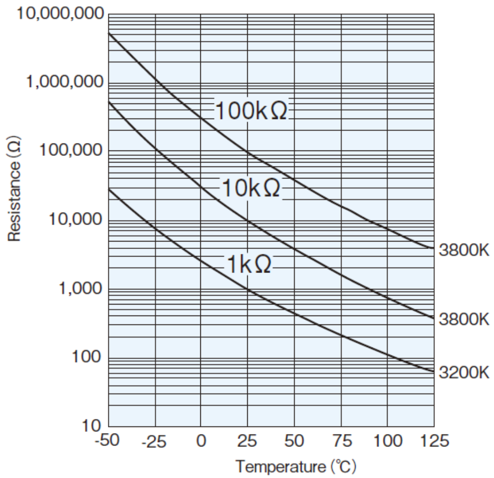
# Significant Features

- High sensitivity
  - Larger resistor-temperature coefficient =-2.8～-5.1%/°C
- Easy fabrication
  - Various shapes, miniaturization available
- Wide range of selectable resistor value
  - Tens of Ω～several hundreds kΩ

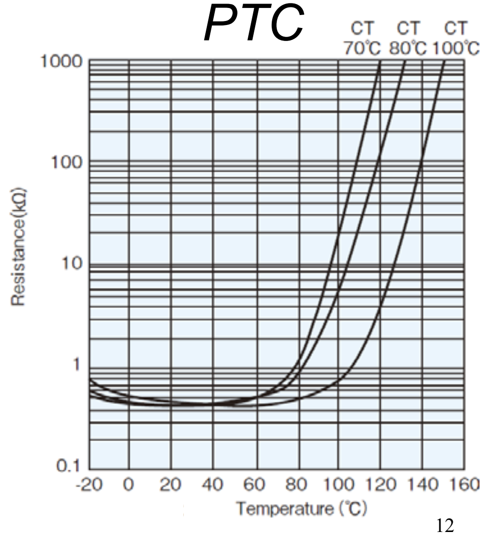


# Characteristic Curves

*NTC*




*PTC*



# Temperature Coefficient

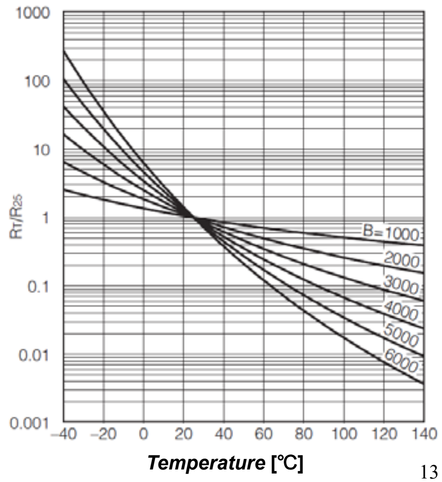
- $T_0$: reference temperature, usually 298.15K (25°C)
- $R_0$: resistance at $T_0$
- B: thermistor constant

  $=E_g/2k=1500\sim6000\text{K}$

$$R(T)=R_0\exp\left[B\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$$

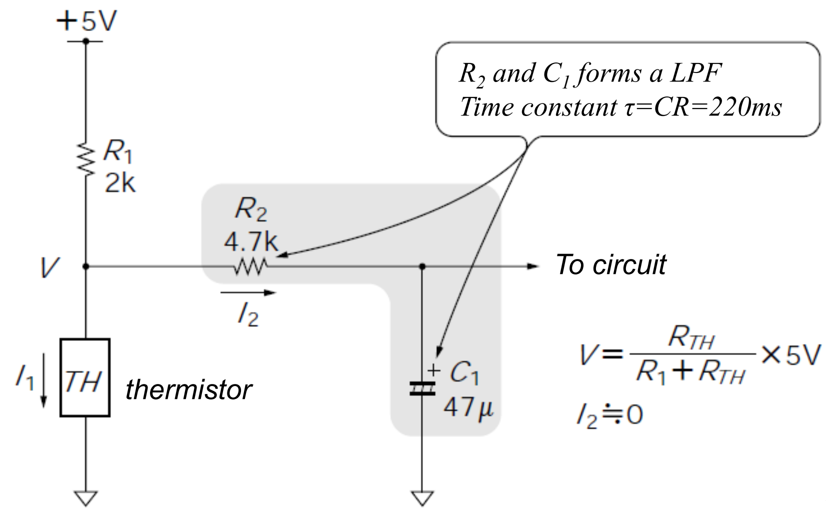
- α: temperature coefficient

$$\alpha=\frac{1}{R}\frac{dR}{dT}=\frac{d}{dT}\left(\frac{B}{T}\right)=-\frac{B}{T^2}$$






# Temperature-Voltage Converter

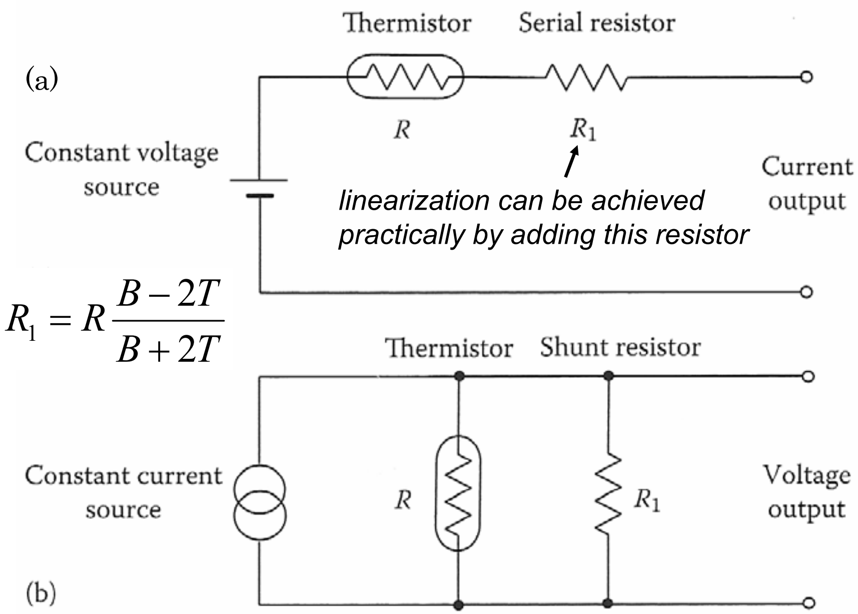



$$V=\frac{R_{TH}}{R_1+R_{TH}}\times5\text{V}$$

$I_2 \fallingdotseq 0$



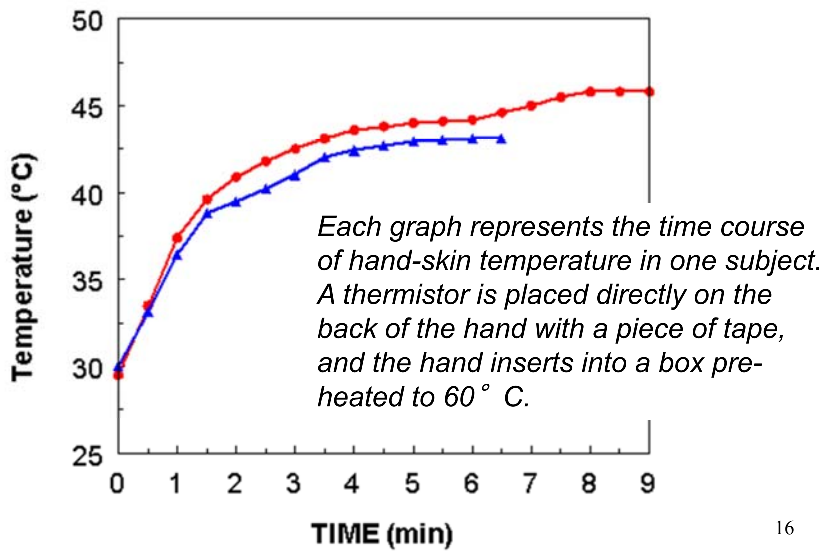
# Linearization Circuits




$$R_1=R\frac{B-2T}{B+2T}$$



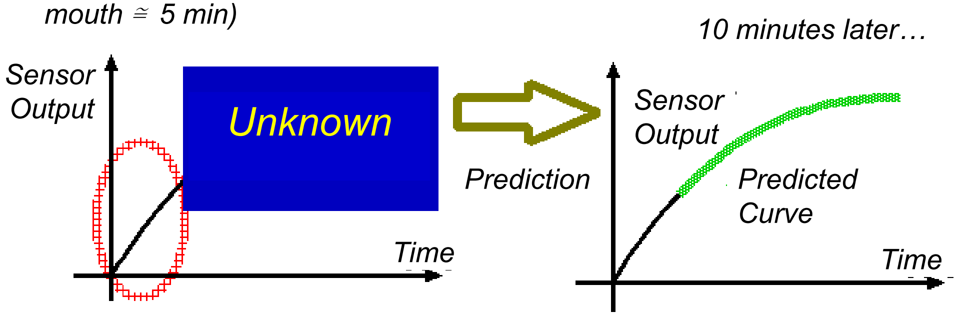
# Thermistor Output vs. Time



# Two Measurement Methods

***Direct method***
*Real temperature measurement is complete at the time of the sensor equal to the body temperature (axilla ≅ 10 min, mouth ≅ 5 min)*

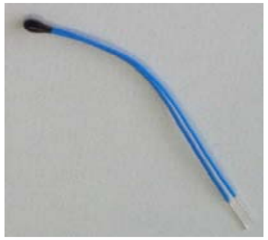
***Predictive method***
*Using an empirical curve, predict the final temperature value from the first 1 min or several tens of sec real measurement.*



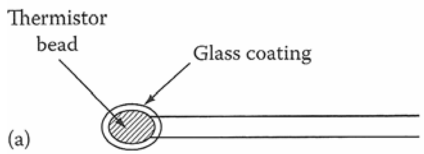

*First 1 min real measurement*



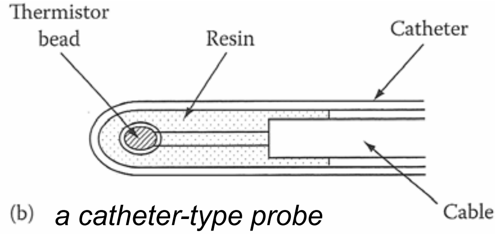
# Thermistor Probes



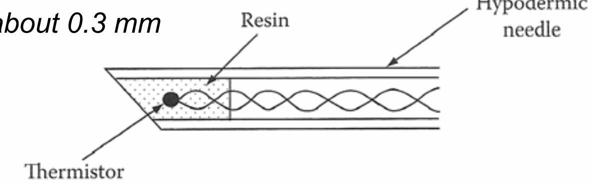
*the thermistor is connected to a flexible insulated cable, and the connected part is also insulated and completely waterproof*




*a glass-coated thermistor bead with bare lead wires. Bead diameter is about 0.3 mm*




(b) *a catheter-type probe*




(c) *a needle-type probe*



# Electronic Thermometers

Basal thermometer
Range 32.00℃～42.00℃
Accuracy ±0.05℃(35.00～38.00℃)
±0.1℃(32.00～34.99℃、38.01～42.00℃)


Medical thermometer
Range 32.0℃～42.0℃
Accuracy ±0.1℃

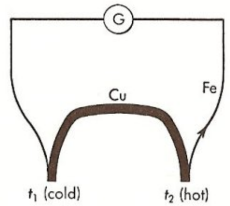
BBT increases 0.3～0.5℃ in ovulation day and shifts from low temperature to high temperature



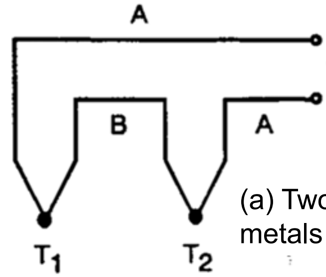
# Thermocouple

*thermoelectric sensor*

***Seebeck effect** = a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances.*



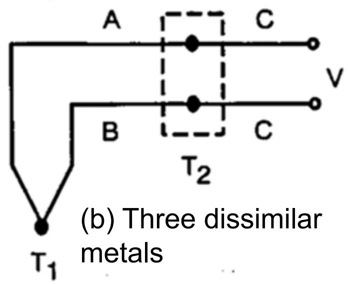

*Sensitivity between* 20ºC to 40ºC:
*41 μV/K for copper/constantan*
*40 μV/K for chromel/alumel*
*6.1 μV/K for platinum/rhodium*




(a) Two dissimilar metals

***Electromotive force*** *depends on the* ***temperature difference*** *between two* ***junctions***

When the temperature of the reference junction $T_2$ is kept constant, electromotive force $V$ varies only with the temperature of the measurement junction $T_1$

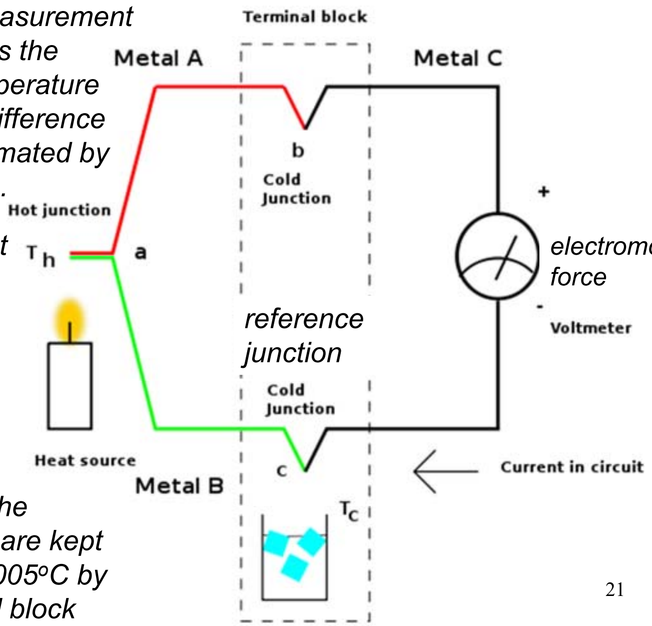



(b) Three dissimilar metals

*a third metal C is connected to both metals A and B, and as long as two new junctions are at the same temperature, it provides the same electromotive force as that of the (a), regardless of the material of the third metal.*

# Thermocouple Circuit

*Temperature of the measurement junction is measured as the reference junction temperature plus the temperature difference between junctions estimated by the electromotive force.*




*measurement junction*

*electromotive force*

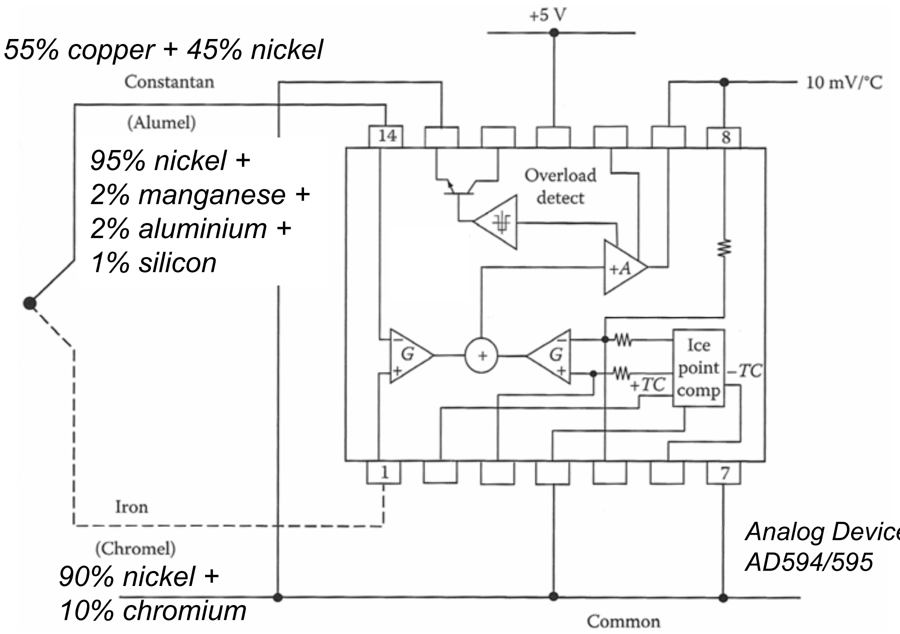
*reference junction*

*Temperature Tc of the reference junctions are kept stable at 0.01±0.0005°C by ice bath for terminal block*



# Thermocouple IC

*55% copper + 45% nickel*




*95% nickel + 2% manganese + 2% aluminium + 1% silicon*

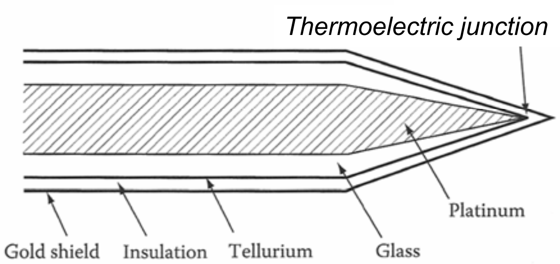
*90% nickel + 10% chromium*

*Analog Devices AD594/595*



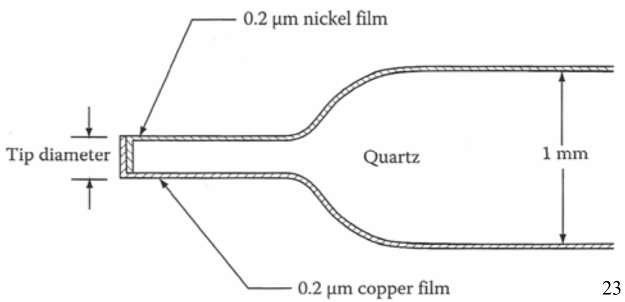
# Micro Thermocouple

*local temperature measurement*



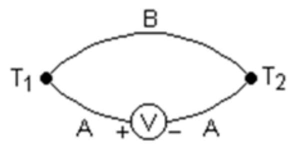

*Junction is about 1 um, made of glass-coated microelectrodes. a tip of thin platinum wire 25 um in diameter was tapered, and a thin glass coating on the platinum was made leaving an exposed cone of platinum. A thin film of tellurium was formed, insulated by coating with a thin film of negative photoresist, and finally a gold film was formed to shield it from electromagnetic interference.*

*A quartz rod was tapered to form a tip of about 10 um in diameter.*
*A nickel layer was vacuum deposited on one side and a copper layer on the other, with two metals overlapping only at the tip end.*
*Finally, the probe was coated with polymer for insulation.*

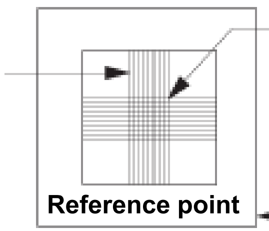





# Thermopile

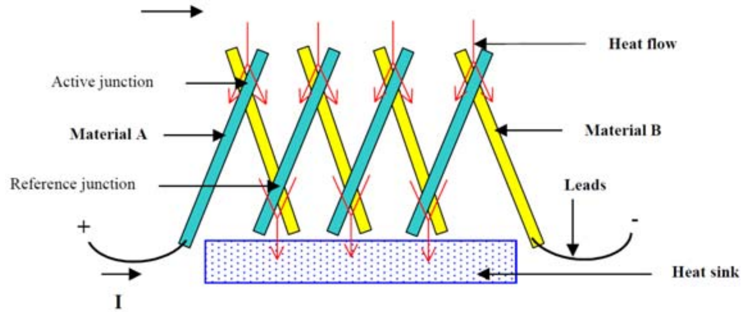



***Thermocouples* in series or in parallel**




**Hot junction**

**Cold junction**




# p-n Junction Sensor

*The voltage V across a **p-n junction** at constant forward-bias current has **linear dependency** on the absolute temperature T.*
*Any diode or transistor can be a temperature sensor.*

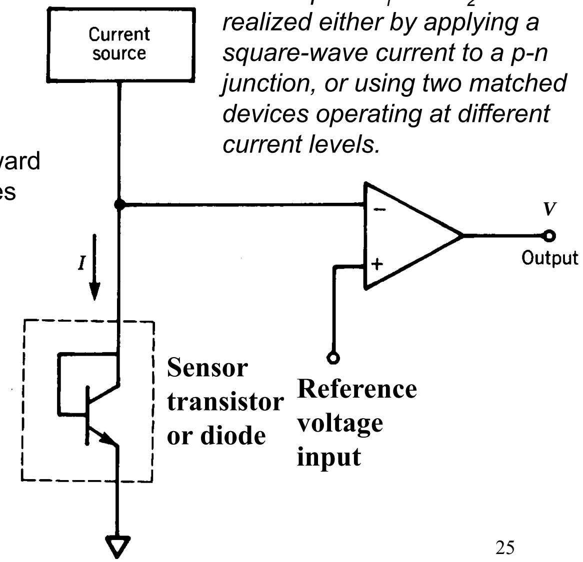
$$I = Ae^{\frac{qV - E_g}{kT}}$$

If the p-n junction in a diode or transistor is driven by different forward current levels $I_1$ and $I_2$, and voltages $V_1$ and $V_2$ are developed at these current levels

$$V_1 - V_2 = \frac{kT}{q}\ln\frac{I_1}{I_2}$$

*I = forward bias current*
*A = constant depending on the geometry of the junction*
*q = electron charge*
*V = voltage across the junction*
*Eg = band gap energy*
*k = Boltzmann constant*
*T = absolute temperature*

*Two outputs $V_1$ and $V_2$ can be realized either by applying a square-wave current to a p-n junction, or using two matched devices operating at different current levels.*



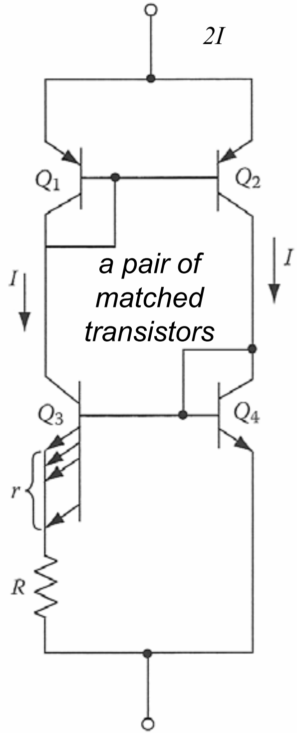



# Two-terminal Current-output Sensor

If transistors $Q_1$ and $Q_2$ are assumed to be equal and have a large gain, their collector currents are equal and constrain the collector current of $Q_3$ and $Q_4$.
$Q_3$ has $r$ base-emitter junctions, and each one is identical to that of $Q_4$.

*I = forward bias current*
*R = bias resistor*
*q = electron charge*
*r = number of base-emitter junctions*
*k = Boltzmann constant*
*T = absolute temperature*

$$V = R \cdot I = \frac{kT}{q}\ln r$$





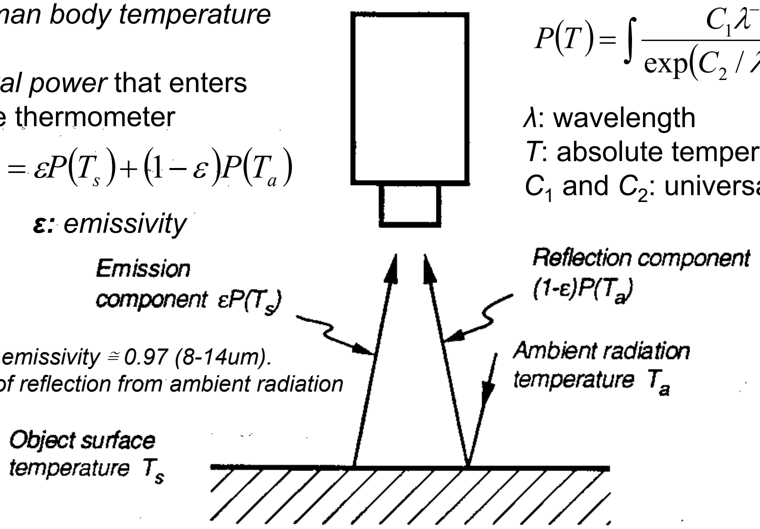

# Infrared Radiometer

*thermal radiation power emitted from the human body is used to measure human body temperature*

*total power* that enters the thermometer

$$W = \varepsilon P(T_s) + (1-\varepsilon)P(T_a)$$

***ε**: emissivity*




*skin emissivity ≅ 0.97 (8-14um).*
*3% of reflection from ambient radiation*

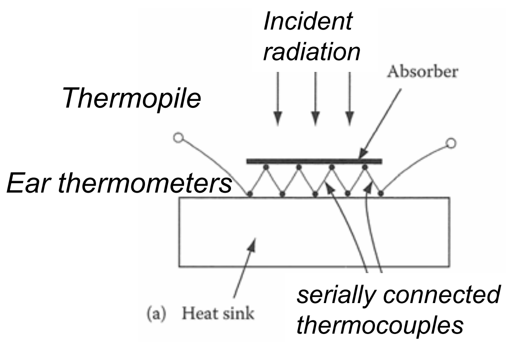
Planck's radiation formula

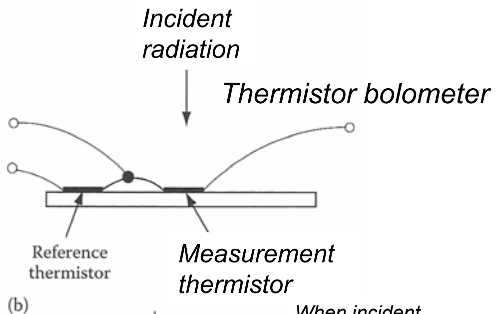
$$P(T) = \int \frac{C_1\lambda^{-5}}{\exp(C_2/\lambda T) - 1}d\lambda$$

$\lambda$: wavelength
$T$: absolute temperature
$C_1$ and $C_2$: universal constants

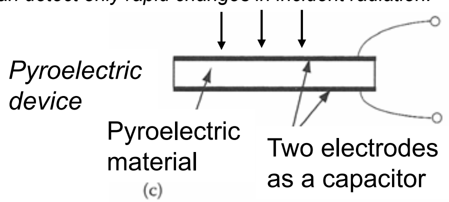


# Thermal Detectors

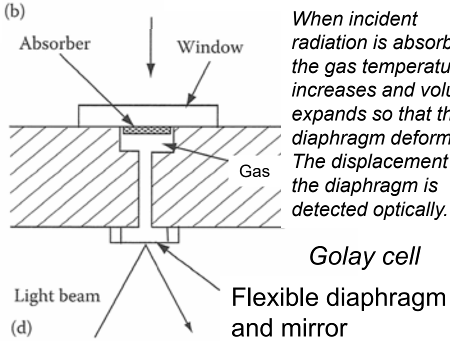


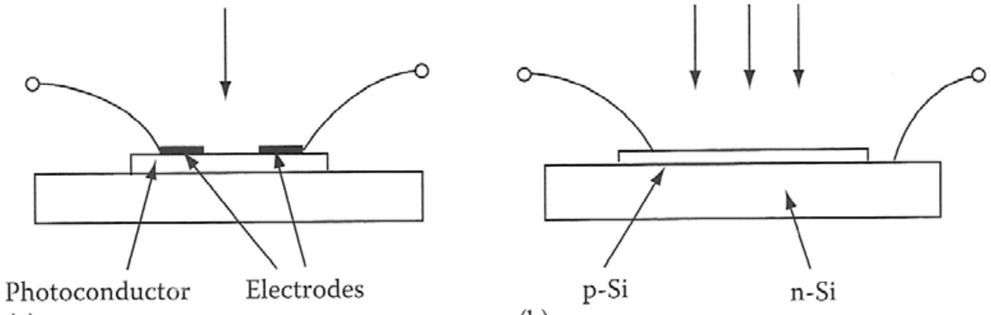

*When the temperature changes, charge appears and potential develops. The potential decays due to the discharge when the temperature balances. It can detect only rapid changes in incident radiation.*




*When incident radiation is absorbed, the gas temperature increases and volume expands so that the diaphragm deforms. The displacement of the diaphragm is detected optically.*



# Photon Detectors




*Photoconductor*

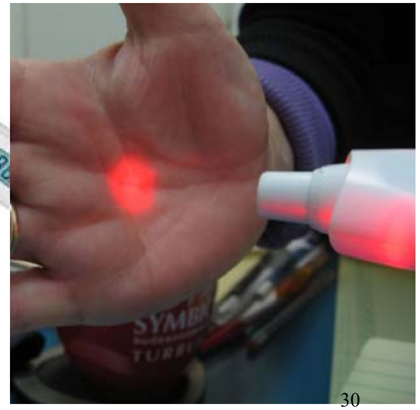
Carriers that are electron-hole pairs are generated by incident photons when the photon energy exceeds the band gap energy. Generated carriers create a photo current when a potential is applied externally. Carriers are also generated by thermal energy and this results in a dark current in the entire frequency range. Dark current can be reduced by cooling the detector.

*Photodiode*

A p-n junction operated under reverse bias.
At the boundary of the p and n region, there is a depletion region where carrier density is zero. When an electron-hole pair is generated in a depletion region by an incident photon, the electron and hole are separated and generate an electric current in the external circuit.

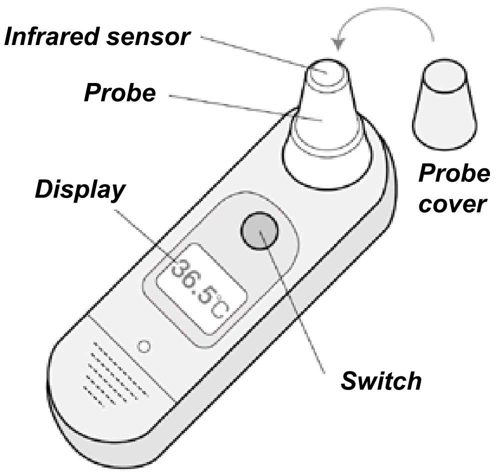


# Infrared Skin Thermometer



# Infrared Tympanic Thermometer

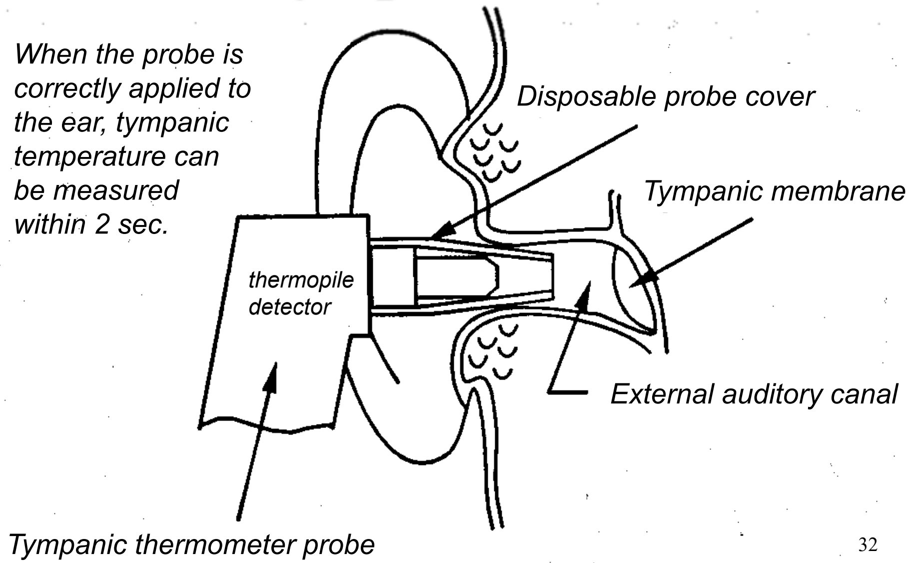






# Infrared Tympanic Thermometer

*When the probe is correctly applied to the ear, tympanic temperature can be measured within 2 sec.*



http://techon.nikkeibp.co.jp/english/NEWS_EN/20110117/188796/

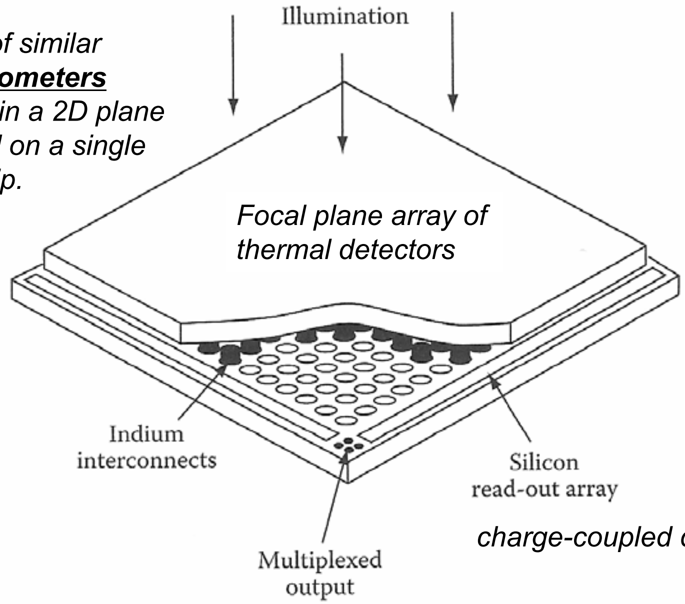
# Thermo Mirror

*It captures the temperature via a built-in infrared sensor in a mirror.*
*By looking at the mirror and your temperature will be measured automatically.*




# Infrared Image Device

*A matrix of similar **microbolometers** arranged in a 2D plane fabricated on a single silicon chip.*




*charge-coupled device*



# Thermo Camera

*Infrared thermography provides thermal images by thermo camera. It realizes a noncontact measurement.*

*To obtain a thermal image of an object, surface temperature at many points on the object should be measured.*

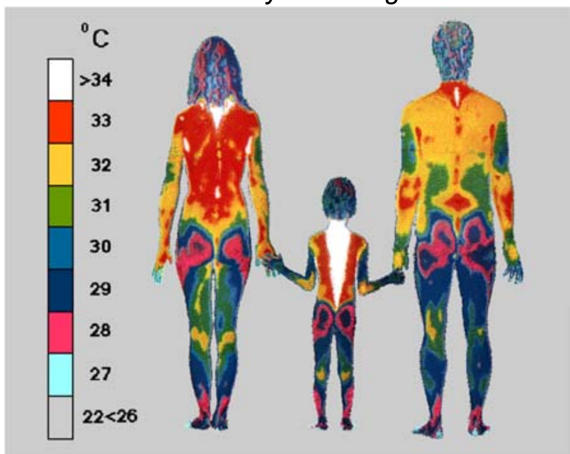

*This is achieved by either mechanical scanning by means of moving mirrors or prisms, or by electronic scanning of the infrared detectors placed at the focal plane.*

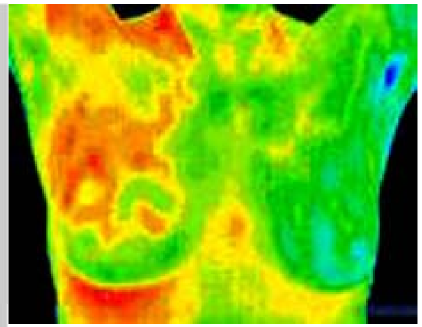
*Raytheon, Radiance MS*



# Thermogram and Breast Cancer

*Whole Body Thermogram*



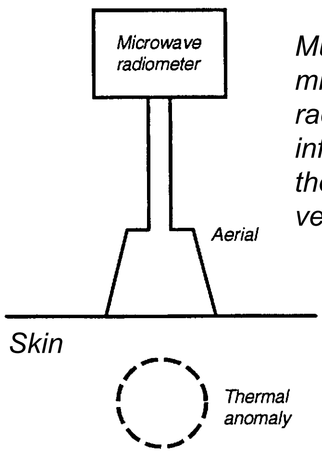
*An abnormal thermogram is a significant indicator for breast cancer*

A major mechanism involved with all degenerative disease is inflammation. Inflammation is present in precancerous and cancerous cells, in torn muscles, ligaments and arthritic joints. Heat is an indication of inflammation. Thermography measures inflammation and deficiencies in the body due to various dysfunctions such as diabetes, heart disease and some cancers.

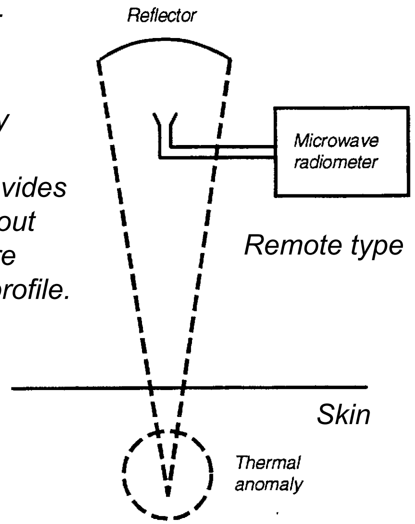
# Microwave Thermometer

***Active microwave*** *imaging method estimates local temperatures in the body from a reconstructed image of the temperature-dependent dielectric constant of the tissue.*
***Passive microwave*** *imaging method obtains thermal images from the deep tissue by thermal radiation in the microwave range.*

*Contact type*




*Multi frequency microwave radiometer provides information about the temperature versus depth profile.*






the amount of heat that *passes through the plate per unit time and unit area*

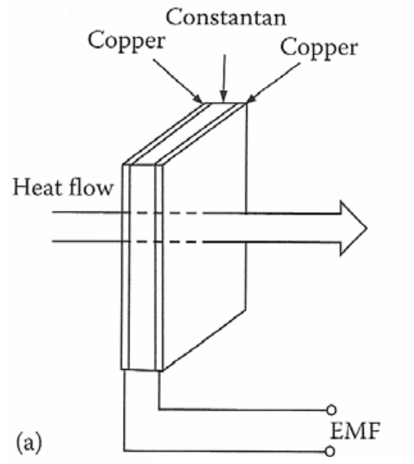
# Heat Flow Measurement

*estimate heat loss from the body, or efficiency of thermal insulation of clothes or animal fur*

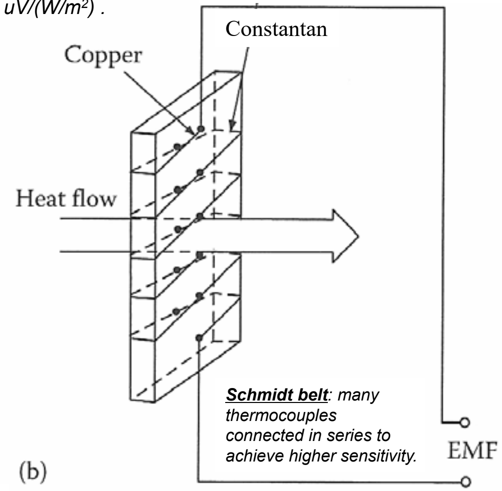
*heat flow Q = k$\Delta$T/d*
*k: thermal conductivity*
*d: thickness of the plate*
*$\Delta$T: temperature difference across the plate*

*a constantan plate of 5 mm is coated by copper on both sides, its sensitivity is only about 0.083 uV/(W/m$^2$).*
*a tellurium-silver alloy of 1.5 mm coated on its two sides with copper provides about 6.9 uV/(W/m$^2$) .*

*thermocouple wire is wound spirally on a strip having adequate thermal resistance, so that every half-turn of each spiral consists of constantan wire, and the other half-turn consists of copper wire.*




*Thermal Electromotive Force*




***Schmidt belt**: many thermocouples connected in series to achieve higher sensitivity.*

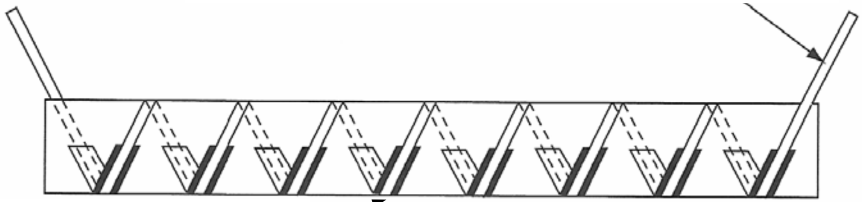


# Schmidt-belt Heat Flow Sensor

*Copper and constantan ribbons are connected in parallel at every half-turn, and thus loop current may be generated if a temperature gradient along this half-turn is developed.*

*A copper ribbon is cut and applied to a paper-board strip*

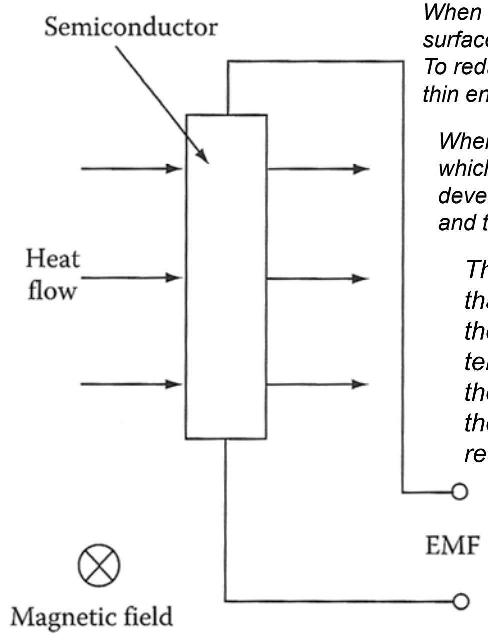
*Constantan ribbon is then wound over the copper*



*Junctions are soldered*



# Nernst Effect Principle



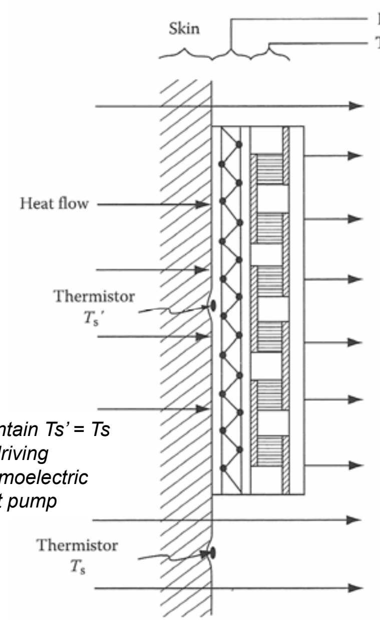

*When a heat flow sensor is attached to the object surface, natural heat flow distribution may be disturbed. To reduce this effect, the heat flow sensor should be thin enough → **transverse thermomagnetic** technique*

*When heat flows through a semiconductor plate to which a transverse magnetic field is applied, EMF is developed perpendicular to the direction of heat flow and the magnetic field.*

*The advantage of using the Nernst effect is that the output EMF is proportional not to the temperature difference but to the temperature gradient. For a given heat flow, the temperature gradient is independent of the thickness, so thermal resistance can be reduced without reducing sensitivity.*

*The disadvantage of using an external magnetic field is that this limits most applications of this technique, thus is used only in thermal radiation detectors*

# Body Surface Measurement




*Maintain Ts' = Ts by driving thermoelectric heat pump*

*The insulating effect due to the thermal resistance of the heat flow sensor is compensated for by placing a servo-controlled thermoelectric heat pump on the outer surface of the sensor*

*The temperature at the inner surface of the sensor can be equated to the temperature at the uncovered skin adjacent to the sensor. In a steady state, heat flow toward the skin surface where the sensor is placed will be the same as that at the uncovered skin, as long as the temperatures at these two sites are the same.*

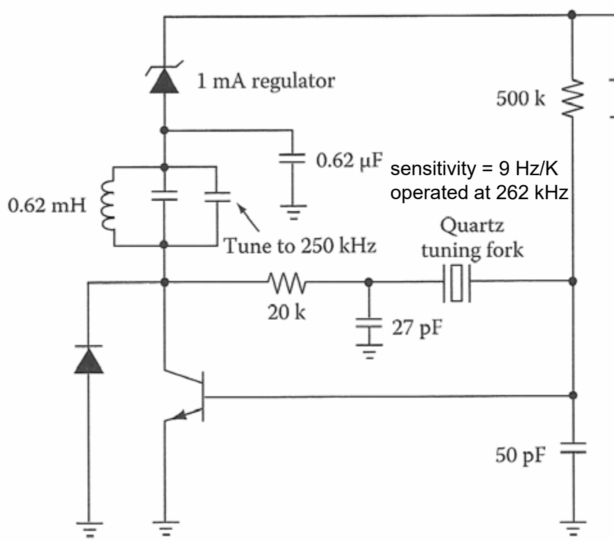
$$H_{corr} = \frac{H_{meas}\Delta T_1}{\Delta T_2 - RH_{meas}}$$

*$H_{corr}$: corrected heat flow.*
*$H_{meas}$: measured heat flow.*
*R: thermal resistance*
*$\Delta T_1$: temperature difference between the uncovered skin adjacent to the sensor and an ambient reference*
*$\Delta T_2$: temperature difference between the area under the surface of the sensor and the ambient reference*

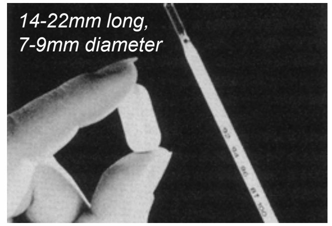


*body core temperature in the digestive tract*

# Swallowable Capsule

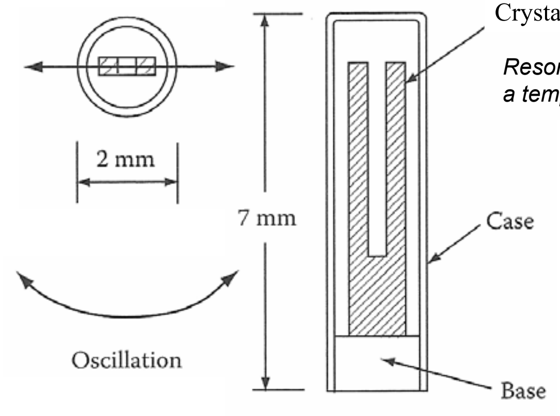



sensitivity = 9 Hz/K
operated at 262 kHz






# Quartz Crystal Resonator



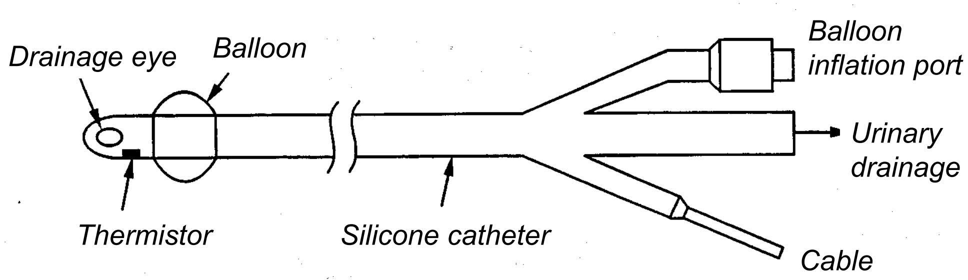

*Resonant frequency of a quartz resonator has a temperature coefficient (10 and 100ppm/K)*

*A crystal resonator can be excited by ultrasound, and its resonant frequency can be determined by using an ultrasonic coupling.*
*When an ultrasound near the resonant frequency is applied, the resonator crystal is excited and after the applied wave is terminated, the resonation decays and emits an ultrasonic wave of the resonant frequency into the surrounding medium. The induced ultrasound can be detected at a distant site and thus this technique provides remote of temperature in a medium in which sound can propagate.*

*Its resonant frequency is about 40kHz with a temperature coefficient of about 3.2Hz/K. To measure temperature, the resonator is excited for about 0.4 s by applying an ultrasonic wave near the resonant frequency.*
*The damped oscillations in the resonant frequency are measured. The absolute accuracy is about 0.1°C, with temperature resolution about 0.01°C. It has been shown that when the capsule is swallowed, temperature measurements can be performed from the abdominal skin surface.*



# Thermistor-tipped Foley's Bladder Catheter



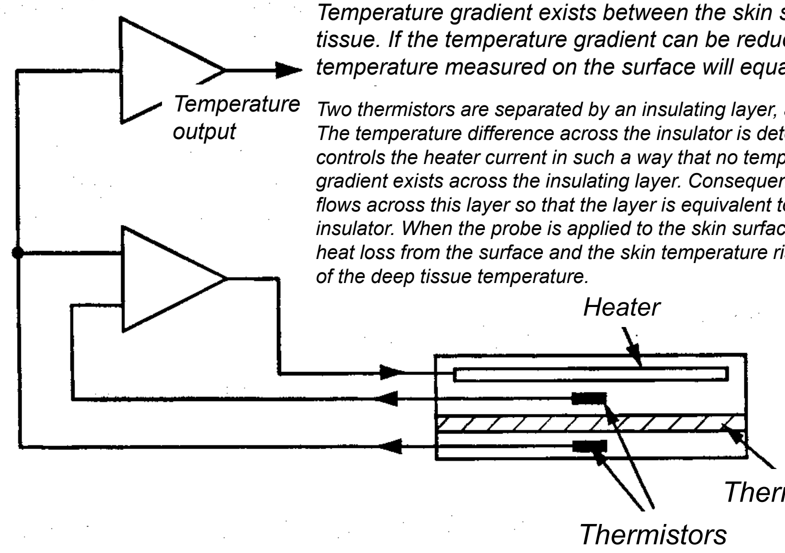
Body core temperature is monitored at deeper sites of the body such as the rectum, esophagus, and bladder using **indwelling thermometer probes**.

# Zero-heat-flow Thermometer

*measurement of deep body temperature* ***from the skin surface***

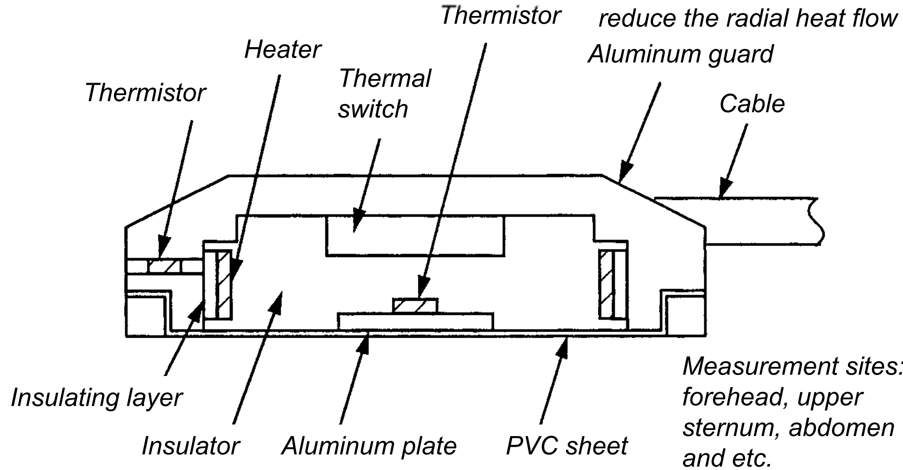
*Temperature gradient exists between the skin surface and deep tissue. If the temperature gradient can be reduced to be zero, temperature measured on the surface will equal to deep tissue.*

*Two thermistors are separated by an insulating layer, and a heater. The temperature difference across the insulator is detected and controls the heater current in such a way that no temperature gradient exists across the insulating layer. Consequently, no heat flows across this layer so that the layer is equivalent to an ideal insulator. When the probe is applied to the skin surface it prevents heat loss from the surface and the skin temperature rises to the level of the deep tissue temperature.*






# Zero-heat-flow Probe




*Measurement sites: forehead, upper sternum, abdomen and etc.*

*The initial response time when the probe is applied to the exposed skin is 15 to 20min. After thermal equilibrium is reached, the probe temperature follows physiological changes in core temperature.*



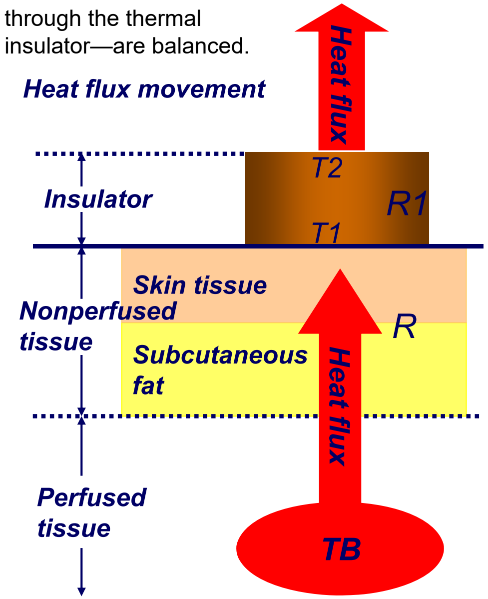
# Deep Body Thermometer

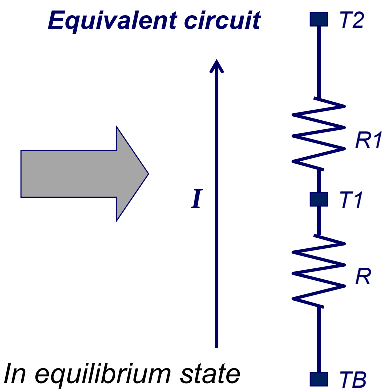
*1.5 to 8 cm in diameter*




# Heat Flux Model

when the body surface is covered with a thermal insulator and the temperature reaches equilibrium, two heat fluxes—one flow from the deep body tissue to the body surface beneath the thermal insulator and the other flow through the thermal insulator—are balanced.



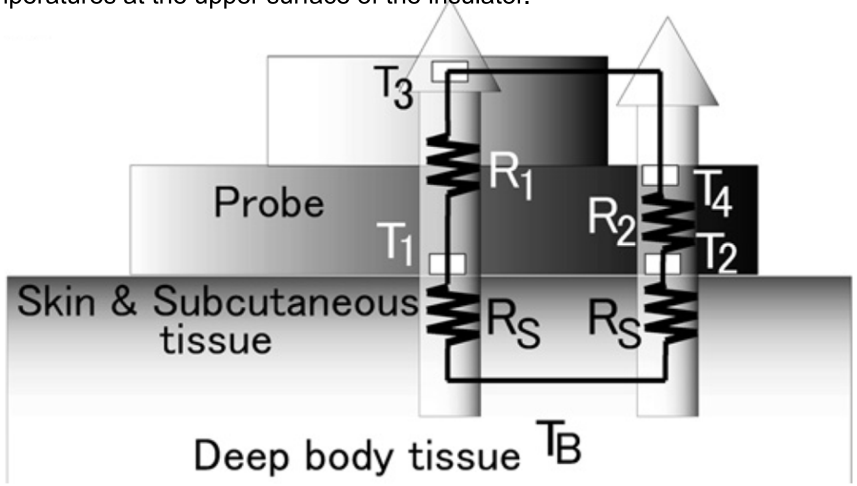

*In equilibrium state*

$$I = (T_1 - T_2)/R_1 = (T_B - T_1)/R$$

$$T_B = T_1 + \frac{(T_1 - T_2)R}{R_1}$$

# Dual-Heat-Flux Circuit Model

Body surface is covered with 2 kinds of heat insulators with thermal resistances $R_1$ and $R_2$.
$R_S$ is the thermal resistance of the skin and subcutaneous tissue;
$T_1$ and $T_2$ are the skin temperatures beneath the insulator, and $T_3$ and $T_4$ are the temperatures at the upper surface of the insulator.






# Estimation of Deep Temperature

$$T_B = T_1 + \frac{(T_1 - T_3)R_S}{R_1} \qquad T_B = T_2 + \frac{(T_2 - T_4)R_S}{R_2}$$

*Suppose both Rs identical*
*Define $K=R_1/R_2$ to describe sensor property*

*When the ratio of the thermal resistance K is obtained, we can get the deep body temperature $T_B$ from $T_1$-$T_4$*

$$T_B = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{K(T_2 - T_4) - (T_1 - T_3)}$$

*K* is obtained by a simulation experiment.

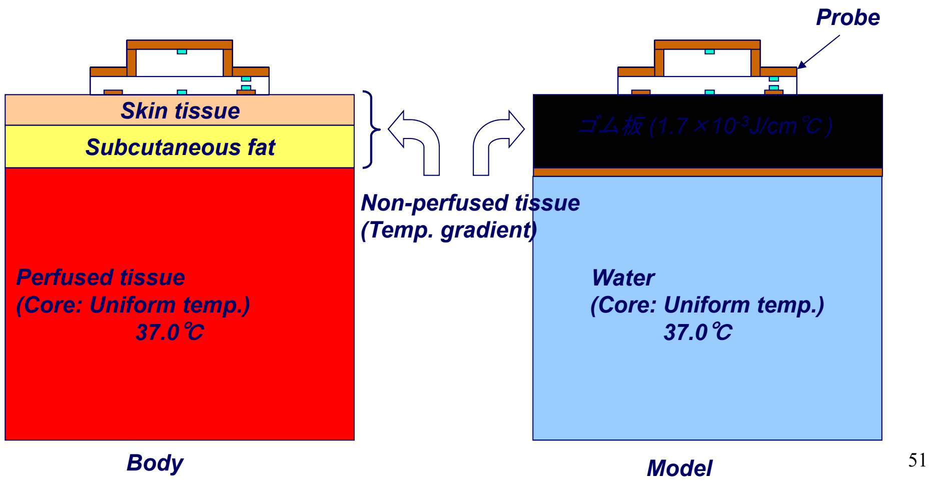
$$K = \frac{(T_B - T_2)(T_1 - T_3)}{(T_B - T_1)(T_2 - T_4)}$$



# Estimation of *K* Value

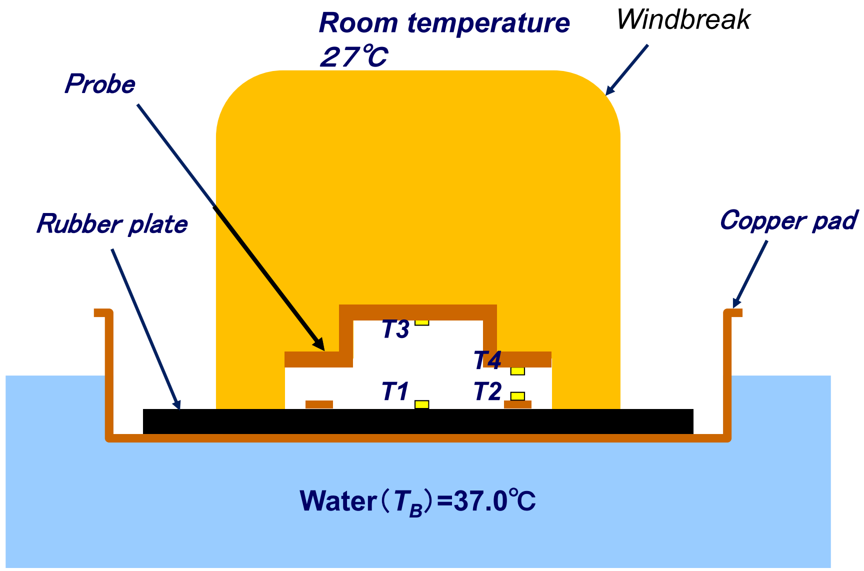
$$K = \frac{(T_B - T_2)(T_1 - T_3)}{(T_B - T_1)(T_2 - T_4)}$$

The probe is set on a rubber sheet that is placed over the inner bottom of a copper vat floating in a water bath where temperature $T_B$ is known.
In equilibrium state, $T_1$-$T_4$ are measured.

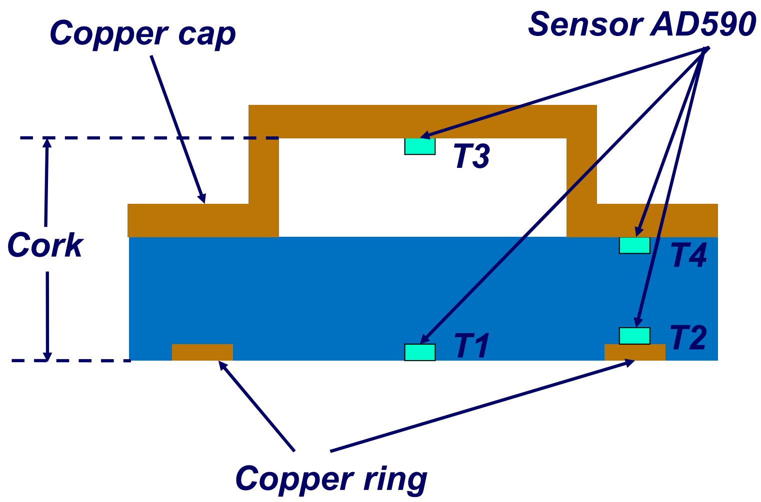





# Simulation Model



# Probe Structure






# Probe Prototype