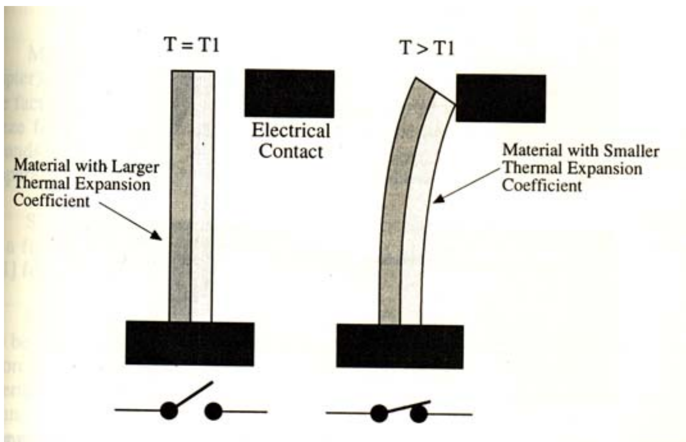
Thermal Sensors

- Thermo-Mechanical Sensors
- Thermoresistive Sensors
- Thermocouples
- Junction-Based Thermal Sensors

Thermo-Mechanical Sensors

$$\alpha_L = \frac{1}{\Delta T}\frac{\Delta L}{L}$$

Coefficient of thermal expansion



Operating principle of thermal bimorph switch

Material	Thermal Conductivity W/cm•K (@300K)	Temperature Coefficient of Expansion, ppm/K
Aluminum	2.37	25.0
Aluminum Oxide (polycrystalline	0.36	8.7
Aluminum Oxide (sapphire)	0.46	-
Carbon, Amorphous	0.016	-
Carbon, Diamond	23	-
Chromium	0.94	6.00
Copper	4.01	16.5
Gallium Arsenide	0.56	5.4
Germanium	0.60	6.1
Gold	3.18	14.2
Iridium	1.47	6.40
Iron	0.80	11.8
Molybdenum	1.38	5.00
Nickel	0.91	13.0
Platinum	0.716	8.8
Polyimide, Amoco Ultradel 1414	-	191
Polyimide, Dupont PI2611D	-	3.00
Polyimide, Hitachi PIQ-3200	-	50.0
Polysilicon	0.34	2.33
Silicon	1.49	2.60
Silicon Carbide	4.90	-
Silicon Dioxide (fused silica)	0.0138	0.4
Silicon Dioxide (thermal)	0.0138	0.35
Silicon Nitride	0.16	1.6
Silver	4.29	18.9
Teflon™ (PTFE)	0.0225	-
Tin	0.67	22
Titanium	0.219	8.6
Tungsten	1.73	4.50

Thermoresistive Sensors

Thermoresistive temperature transducers are based on the fact that the resistance (or resistivity) of most materials changes with temperature.

$$\alpha_R = \frac{1}{\Delta T}\frac{\Delta R}{R}$$

Temperature Coefficient of Resistance

Thermistor

a form of resistive device that possesses a large temperature coefficient of resistance over an extended temperature range.
Typical: 40000-60000ppm/K for NTC thermistor

Classification:

- negative temperature coefficient (NTC) thermistor
- positive temperature coefficient (PTC) thermistor

Material	Resistivity μΩ•cm	Temperature Coefficient of Resistance, ppm/°C
Carbon (graphite)	1,390	-500
Manganin (alloy)	48.2	2
Nichrome	101	1,700
Chromium	12.9	3,000
Aluminum	2.83	3,600
Silver	1.63	3,800
Copper	1.72	3,900
Platinum	10.6	3,927
Tungsten	4.20	4,500
Iron	9.71	6,510
Nickel	6.84	6,900
Gold	2.40	8,300

Resistivity and TCR of some metals

NTC Thermistor

Material:
Sintered mixture of metal oxides of Mn, Ni, Co, Cu, Fe...

Electrical Characteristics:

$\sigma = Nq\mu$

N = density of charge carriers

μ = mobility of the carriers

$\sigma \propto e^{(-E_a/kT)}$ *Ea*: activation energy

$R = R_\infty e^{(E_a/kT)}$

$\alpha = \frac{1}{R}\frac{dR}{dT} = -\frac{E_a}{kT^2}$ TCR

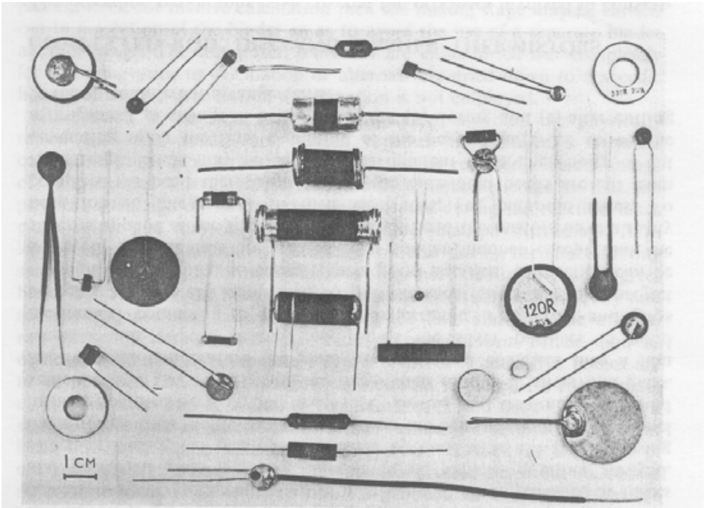
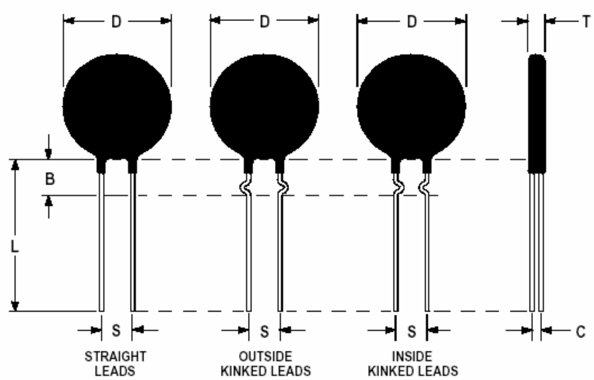


Fig. 2.3 Disc, rod and washer NTC thermistors

AMETHERM
Circuit Protection Thermistors

DATA SHEET

Part Number: NT03 10152



Electrical Specifications:

Zero-Power Resistance @ 25°C	100.0 Ω ± 10%
Resistance @ 0°C/ Resistance @ 50°C	5.60 ± 1%
Resistance @ 25°C/ Resistance @ 125°C	14.1 ± 2%
Beta	3169 ± 2%
Temp Coefficient of Resistance @ 25°C	-3.42%/°C
Operating Temperature Range	-50°C ± 150°C
Maximum Permissible Power	0.45 W
Dissipation Constant	4.0mW/°C
Thermal Time Constant	10 seconds
Material Type	"G"
Max Steady State Current up to 65°C	0.250 A
Resistance @ Max Steady State Current	12.00 Ω
Max Instantaneous Energy	3.0 J

Mechanical Specifications:

D	3.20 mm Max
T	3.20 mm Max
Lead Diameter	0.5 mm Nom
S	3.55 mm Nom
L	38.0 mm Min
Straight Leads	Standard

Vanadium Oxide

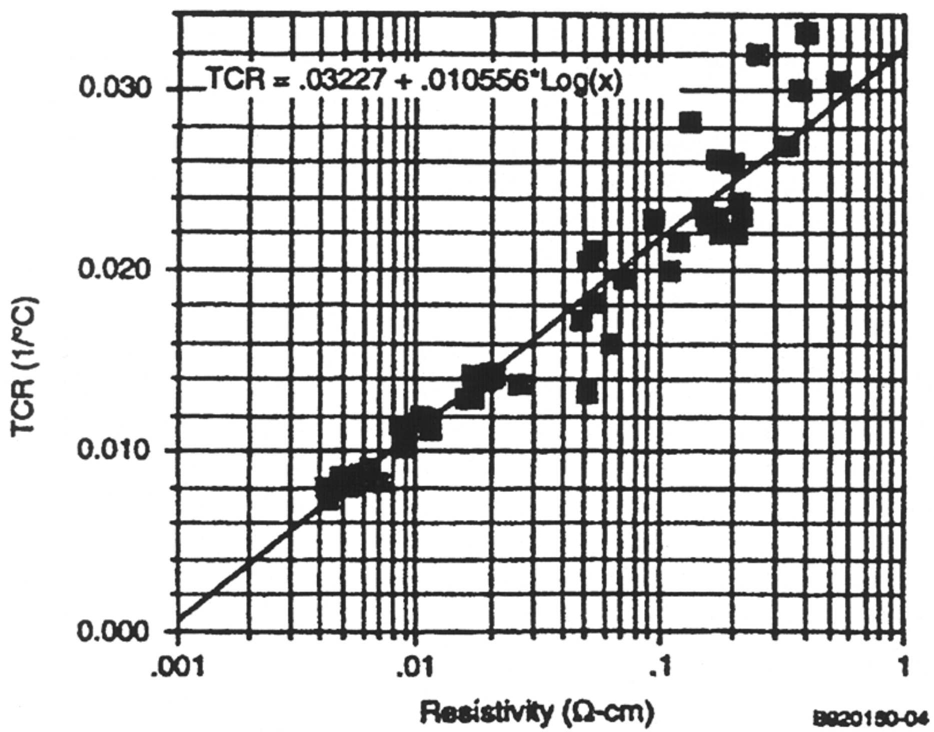


Figure 4-4. Temperature coefficient of resistance (TCR) versus resistivity for thin films of mixed vanadium oxides. From R.A. Wood.[2]

PTC Thermistor

Material: Single crystal silicon or polysilicon

1. Freeze-out Region

$$n = \left(\frac{N_D N_C}{2}\right)^{1/2} e^{\left(-\frac{E_C - E_D}{2kT}\right)} \text{ or } \left(\frac{N_D - N_A}{2N_A}\right) N_C e^{\left(-\frac{E_C - E_D}{kT}\right)}$$

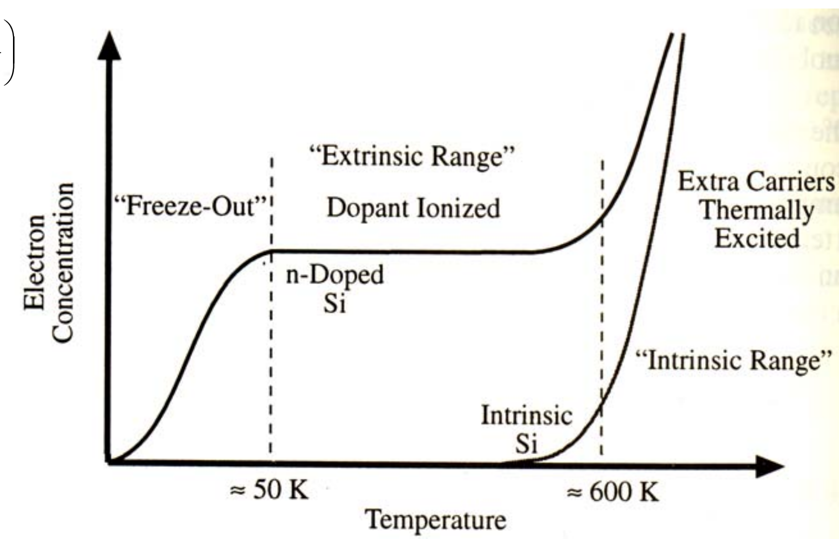
(Depending on compensation conditions)

2. Extrinsic Region (Saturation Region)

$$n = N_D,\ p = n_i^2 / N_D \approx 0$$

3. Intrinsic Region

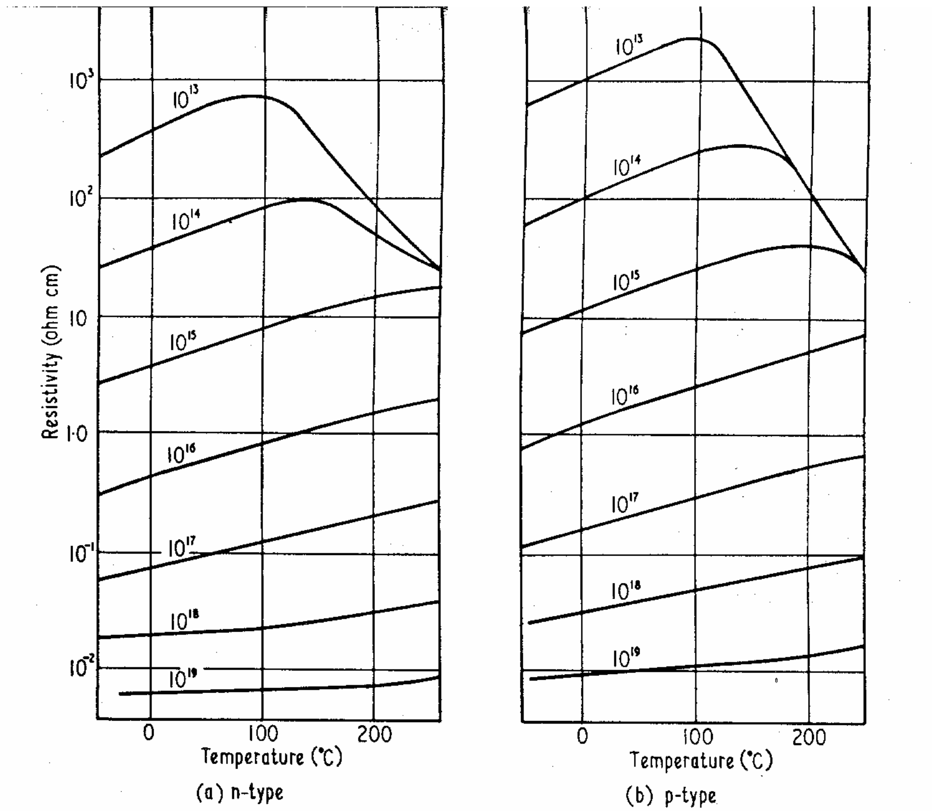
$$n = p = n_i = \left(N_C N_V\right)^{1/2} e^{\left(-\frac{Eg}{2kT}\right)}$$



Electron Concentration - Temperature relationship

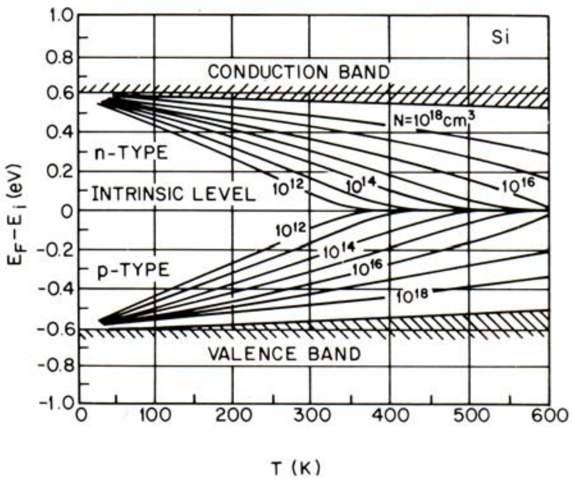
Resistivity of Single Crystal Silicon

$$\rho = (nq\mu_n + pq\mu_p)^{-1}$$



$$\mu_n \propto T^{-2.5}, \mu_p \propto T^{-2.7}$$

(for lightly doped silicon)



Fermi level as a function of temperature and impurity concentration.

Resistivity of Silicon (Nd=10^{15}cm^{-3})

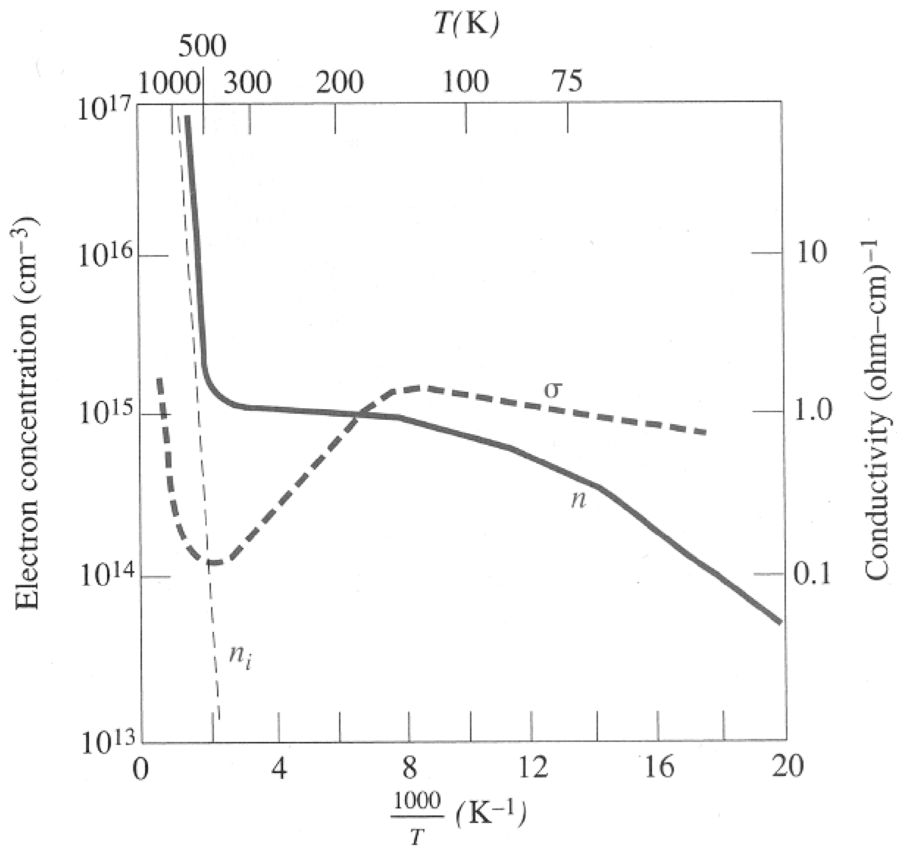


Figure 4.6 Electron concentration and conductivity versus inverse temperature for silicon (After Sze [10])

TCR for single-crystal silicon with usual doping levels: in the order of 0.5%K^{-1}

TCR of amorphous silicon

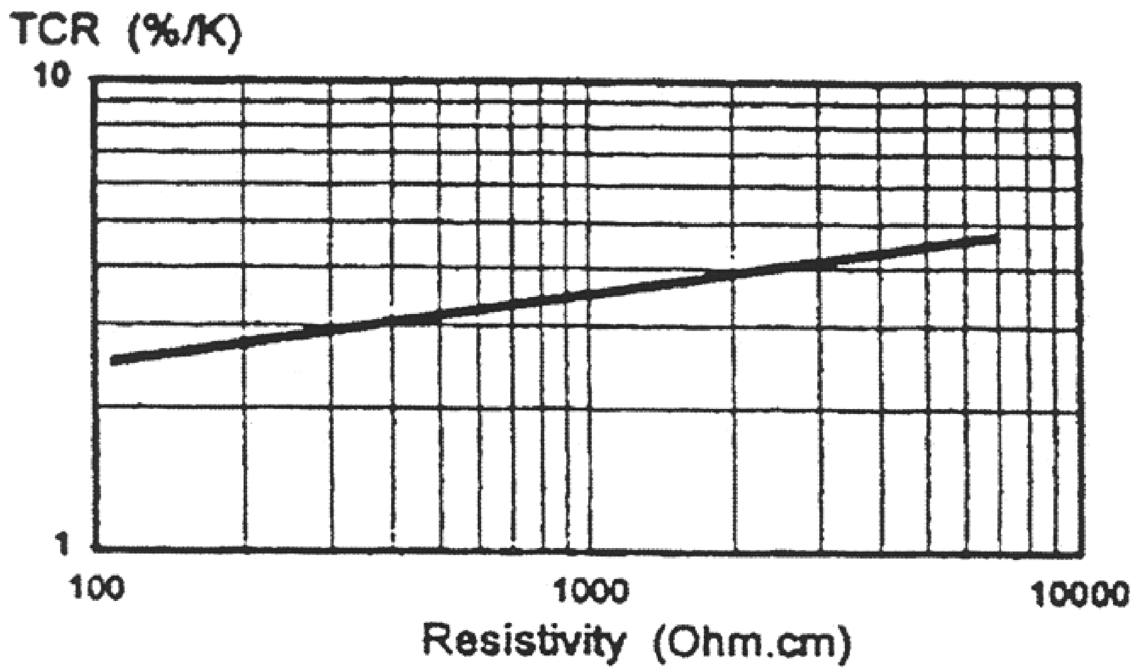


Figure 4-6. Evolution of the TCR as a function of the electrical resistivity of a-Si. From Tissot.[5]

Junction-Based Thermal Sensors

$$I_D = I_S\left[e^{\left(\frac{qV_D}{kT}\right)} - 1\right] \approx I_S e^{\left(\frac{qV_D}{kT}\right)}$$

$$I_S = qA\left(\frac{D_n}{L_n}\frac{n_i^2}{N_a} + \frac{D_p}{L_p}\frac{n_i^2}{N_d}\right)$$

$$n_i^2 = N_C N_V e^{-\frac{E_g}{kT}}, N_C N_V \propto T^3$$

$$I_S(T)/I_S(T_0) = \left(\frac{T}{T_0}\right)^3 e^{-E_g\left(\frac{1}{kT}-\frac{1}{kT_0}\right)}$$

Neglect temperature dependence of *D/L*

$I_S(T), I_S(T_0)$: reverse saturation currents at T and T_0

Approximation : (exponential term dominates)

$$I_S(T)/I_S(T_0) \approx e^{-E_g\left(\frac{1}{kT}-\frac{1}{kT_0}\right)}$$

$$\ln\frac{I_S(T)}{I_S(T_0)} = \frac{E_g}{k}\left(\frac{1}{T_0}-\frac{1}{T}\right) \approx \frac{E_g}{kT_0^2}(T-T_0)$$

I_S doubles per 5 °C

$$\Delta T = T - T_0 = \frac{kT_0^2}{E_g}\ln(2)$$

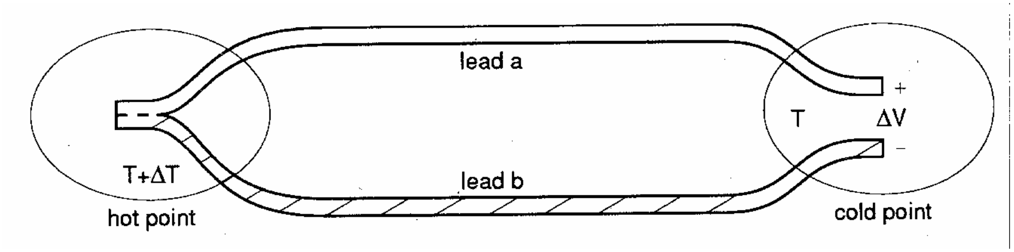
$$\approx \left(\frac{26mV}{1.12V}\right)(300K)\ln(2) \approx 4.83\text{K}$$

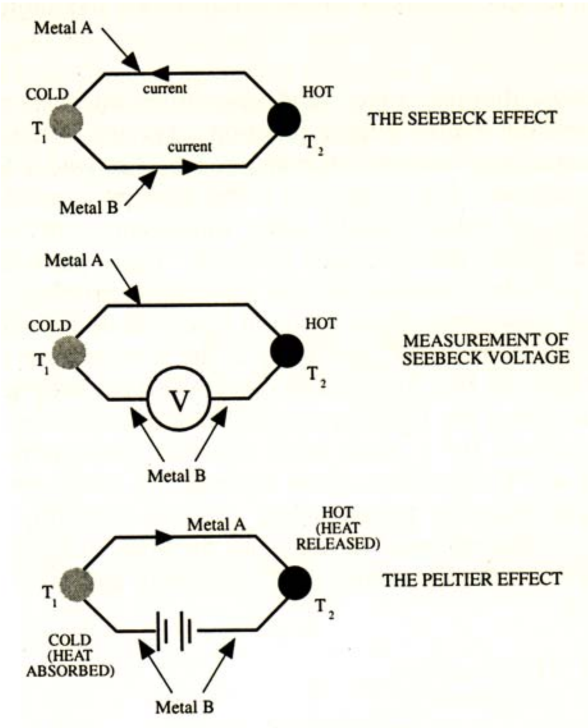
Practical circuit configuration: to measure the voltage across the diode when operated at fixed I_D

$$V_D(T) = \frac{kT}{q}\ln\frac{I_D}{I_S(T)}$$

Thermocouples

Thermoelectric Effect





The Seebeck effect: an emf ΔV is generated due to a temperature difference ΔT

$$\Delta V = \alpha \Delta T$$

α: Seebeck coefficient

Thermocouples

Seebeck coefficient of semiconductor

$$\alpha_n = -\frac{(E_C - E_F) + 2kT}{qT} \qquad \alpha_p = -\frac{(E_F - E_V) + 2kT}{qT}$$

TABLE 2 Seebeck Coefficient for Some Metals and Mono- and Poly-Silicon (in μV/K)

Material	273 K		300 K
p-type mono silicon (Si)			300 to 1000
Antimony (Sb)		43[a]	
Chrome (Cr)	18.8		17.3
Gold (Au)	1.79		1.94
Copper (Cu)	1.70		1.83
Aluminum (Al)			−1.7
Platinum (Pt)	−4.45		−5.28
Nickel (Ni)	−18.0		
Bismuth (Bi)		−79[a]	
n-type polysilicon (Si)			−200 to −500

[a]Averaged over 0 to 100 C.

Blackbody Radiation

Planck Law:

$$E(\lambda,T)=\frac{8\pi hc}{\lambda^5}\frac{1}{e^{(hc/\lambda kT)}-1}$$

Stefan-Boltzmann Law

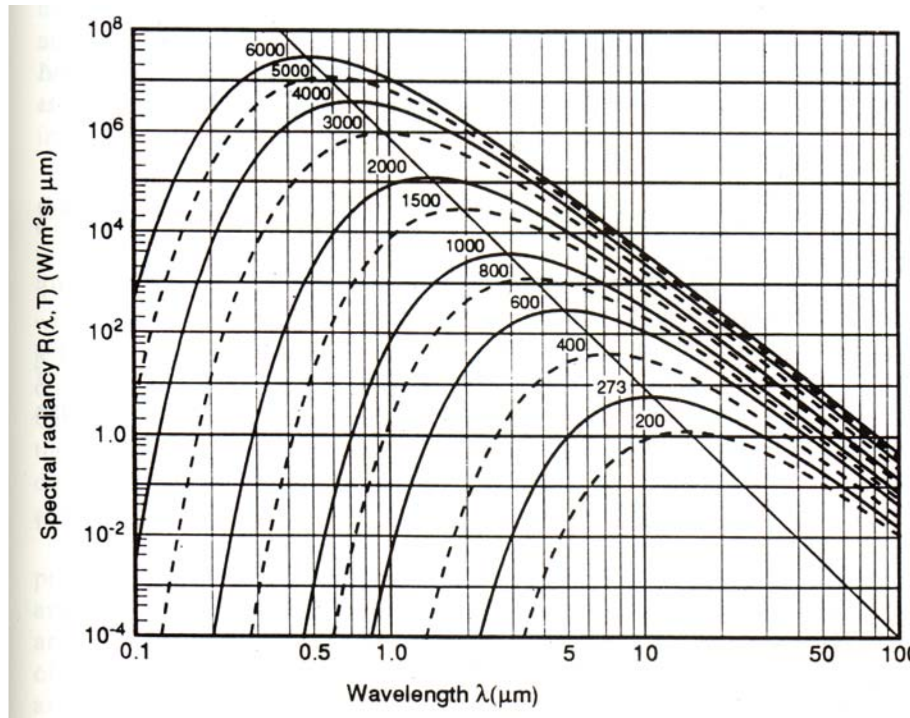
$$P(T)=\varepsilon\sigma T^4$$

$\varepsilon : Emissivity$

$\sigma : 5.67\times10^{-8} Wm^{-2}K^{-4}$

Wien's Displacement Law

$$\lambda_{\max}=\frac{2898}{T}(\mu m)$$



Spectral radiancy (emitted power density) of a black body at given temperature. The diagonal line shows Wien's displacement law

Infrared Detectors

- 2 Categories: Photon detectors, and thermal detectors
- Photon detectors: semiconductors with small bandgap to generate e/h pairs.
  - Photodiodes: InGaAs for near-infrared, HgCdTe, InSb for far-infrared→ needs to be cooled
  - Photoconductors: PbS, PbSe for near-infrared

MODELS

L5910 Infrared Detector	InSb element for operating within 1 µm – 5.5 µm region HgCdTe element for operation within the 4 µm - 20 µm region
L5914 Dual Infrared Detector	InSb and / or HgCdTe element

ACCESSORIES

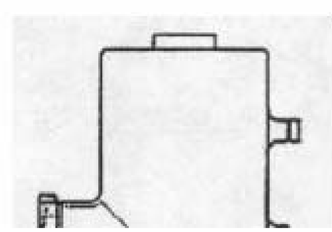
L5930 Detector Mount	For mounting the L5910 and L5914 dewar detectors on a small optical bench baseplate
L5915- X Detector Subassembly - X (1=InSb, 2=HgCdTe)	Additional detector element packages fully interchangeable with existing L5900 dewars

Detector	**Peak ? (microns)**	**50% Cut Off (microns)**		**D * 10 KHz cm/w HZ**	**Active Area**	**Peak ? Responsitivity**
InSb	4.5	2.6	5.4	1.0×10^{11}	1 mm^2	> 2 A/W
HgCdTe	4	2.6	4.2	3.0×10^{11}	1 mm^2	80,000 V/W
HgCdTe	11	5	12	3.0×10^{10}	1 mm^2	3,000 V/W
HgCdTe	16	10	20	5.0×10^{9}	1 mm^2	150 V/W

Peak wavelengths and parameters listed above are typical. Peak wavelengths may be choosen to optionally match your wavelength requirements.

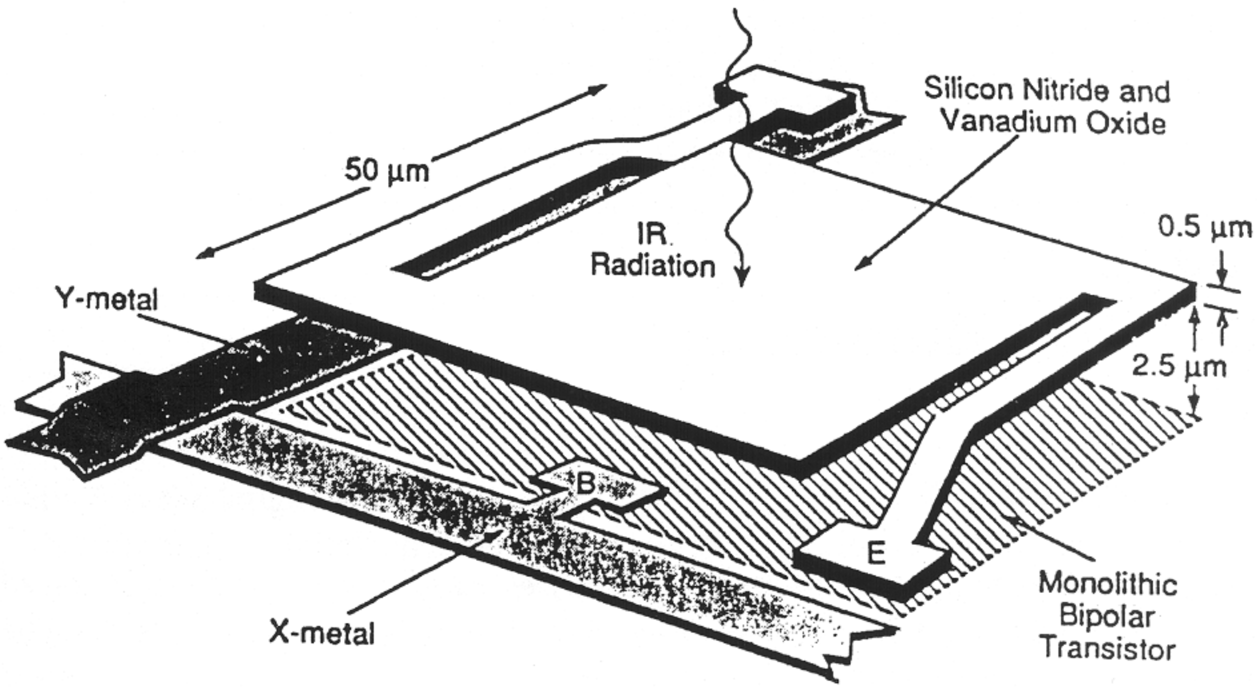
COMMON SPECIFICATIONS

Operating Temperature	77K
Field of View	60°
Bandwidth	1MHz (-3dB)
Preamplifier Power	± (12-15) VDC



Bolometers:Uncooled IR Detector

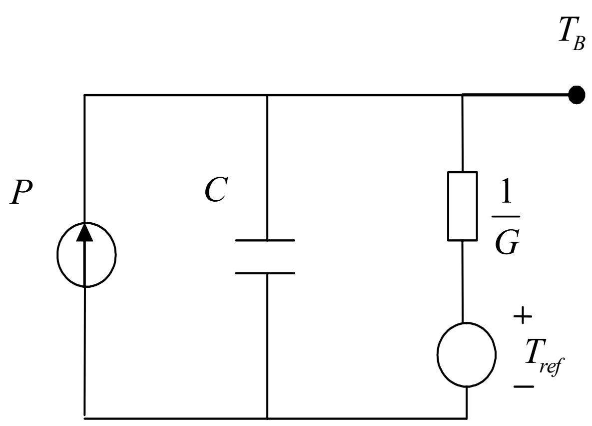
- An absorptive, temperature sensitive element is thermally linked to a temperature reference. As infrared radiation is absorbed, the temperature of the element increases. Measuring the temperature changes gives the incident power.



Thermal Analysis

<u>Thermal equivalents to electrical quantities</u>

Electrical	**Unit**	**Thermal**	**Unit**
Potential	Volt	Temperature	Kelvin
Charge	Coulomb	Energy	Joule
Current	Amp	Power	Joule.Second^{-1}
Current Density	Amp.cm^{-2}	Energy Flux	Joule.Second^{-1}-cm^{-2}
Resistance	Ohm	Thermal Resistance	Kelvin.Watt
Capacitance	Farad	Thermal Capacitance	Joule.Kelvin^{-1}



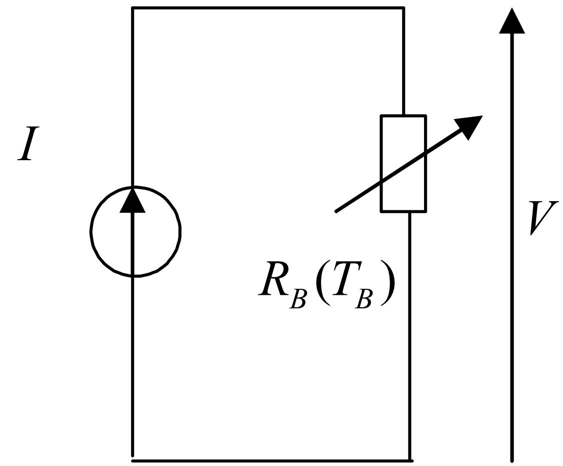
$$P = C\frac{dT_B}{dt} + G\left(T_b - T_{ref}\right) \rightarrow T_B = \frac{P/G + T_{ref}}{1 + j\tau\omega}$$

With $\tau = \dfrac{C}{G}$: time constant

In DC: $\Delta T = \dfrac{P}{G}$

Electrical Readout

$$\Delta V = \alpha R_B I \Delta T = \frac{\alpha R_B I P}{G}$$



Responsivity

$$\mathcal{R} = \frac{\Delta V}{P} = \frac{\alpha R_B I}{G} (A.W^{-1})$$

Figure of Merit for bolometers: <u>NEΔT</u>, Noise-Equivalent Temperature Difference, i.e. the temperature difference on the infrared source that leads to a voltage equivalent to the noise voltage.

Honeywell Infrared Camera

	Honeywell
Pitch	50µm
Fill Factor	70%
Support material	0.8um Nitride
Beam	2Beams: 0.8um Nitride + metal
Beam Lateral Dimensions	2µm *50µm
Thermal Capacitance ($J.K^{-1}$)	$3*10^{-9}$
Thermal Conductance ($W.K^{-1}$)	$2*10^{-7}$
Thermal Time Constant	15ms
Absorptance	80%
Sensing Material	VOx
TCR ($\%K^{-1}$)	2.3
Pixel Resistance	20kΩ
Responsivity ($V.W^{-1}$)	$3.2*10^{5}$
Detector Noise	20µV
Frame Rate"	30Hz
NE∆T (f/1)	39mK