Trasduttori resistivi di temperatura

- Positive thermal coefficient (PTC)
- Negative thermal coefficient (NTC)

anche RTD (Resistive Temperature Detectors), o termistori

PTC (Callendar, van Dusen):

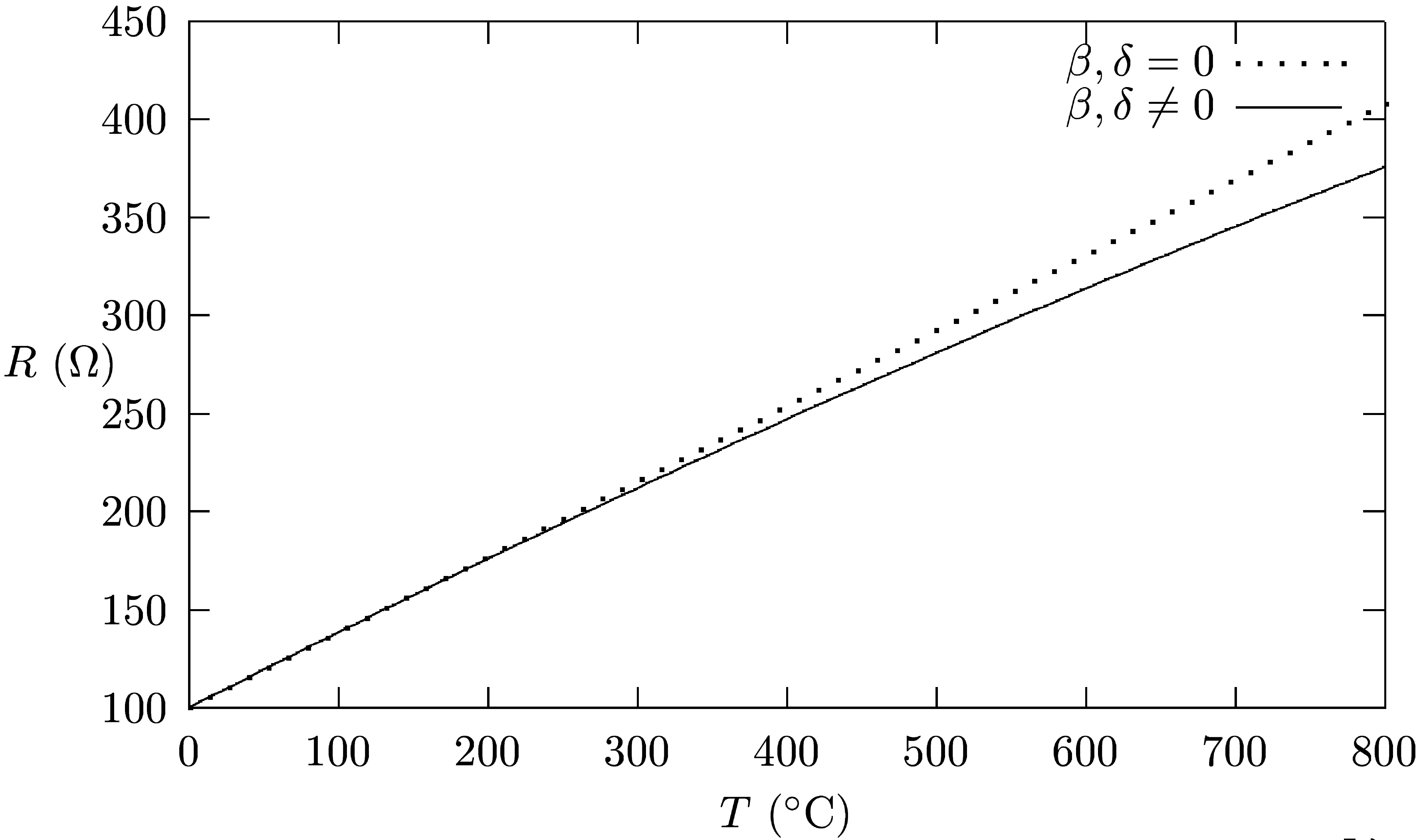
$$R(T) = R_0 \left\{ 1 + \alpha \left[T + \delta \left(1 - \frac{T}{100} \right) \frac{T}{100} \; + \; \beta \left(1 - \frac{T}{100} \right) \left(\frac{T}{100} \right)^3 \right] \right\}$$

$$R_0 = R(0\ ^\circ\mathrm{C})$$

Pt:

$$R_0 = 100\,\Omega, \qquad \alpha = 0.00385\ ^\circ\mathrm{C}^{-1}(\mathrm{Pt}) \qquad \delta = 1.499$$

$$\beta : \text{costante di Van Dusen} : \qquad \begin{array}{lcll} \beta & = & 0 & T < 0^\circ\mathrm{C} \\ \beta & = & 0.10863 & T > 0^\circ\mathrm{C} \end{array}$$



$$R(T) = R_0 \left\{ 1 + \alpha \left[T + \delta \left(1 - \frac{T}{100}\right) \frac{T}{100} \; + \; \beta \left(1 - \frac{T}{100}\right) \left(\frac{T}{100}\right)^3 \right] \right\}$$

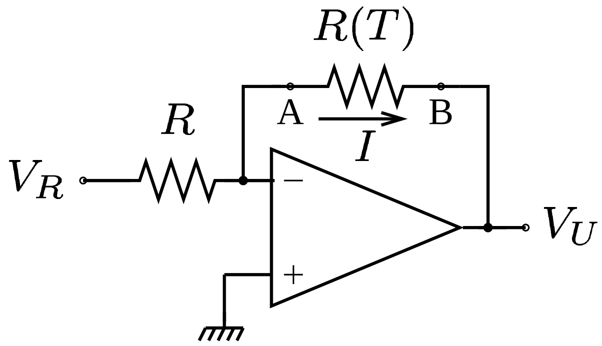
Pt100

$$R(T) = R_0[1 + \alpha(T - T_0)], \quad T < 500^\circ\mathrm{C}$$

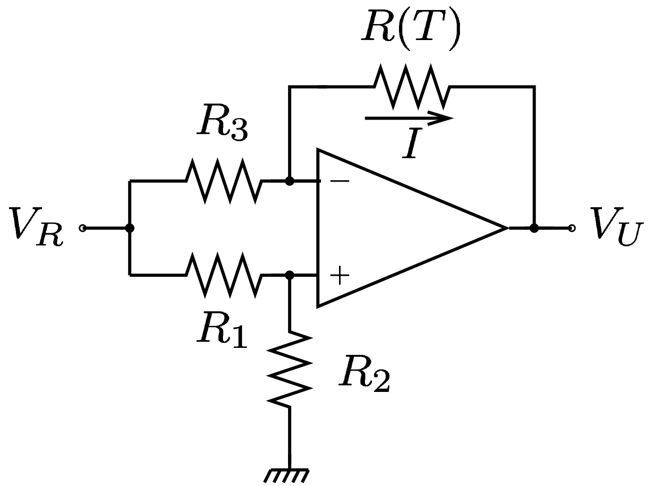
Pt100

- range: $-20^\circ\mathrm{C} \div 500^\circ\mathrm{C}, -50^\circ\mathrm{C} \div 500^\circ\mathrm{C}$
- $\alpha = 0.00385\ \Omega/\Omega/^\circ\mathrm{C}$ ($0.0039\ \Omega/\Omega/^\circ\mathrm{C}$)
- stabilità: drift $< 0.1^\circ\mathrm{C}/$anno
- dimensioni: 1x10 mm circa
- componenti standard, strumentazione “dedicata”

Pt100



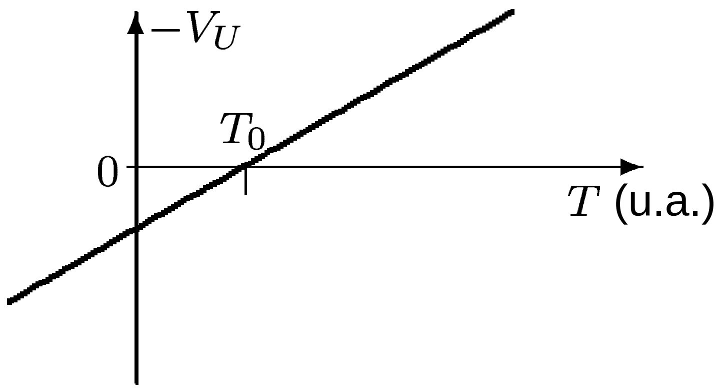
$$I = \frac{V_R}{R}$$, (V_{AB} misurata con A.S.)



$V_U(T_0) = 0$ (bil.)

$$I = V_R \frac{R_1}{R_3(R_1 + R_2)}$$

$$\frac{dV_U}{dT} = -\alpha I R_0$$

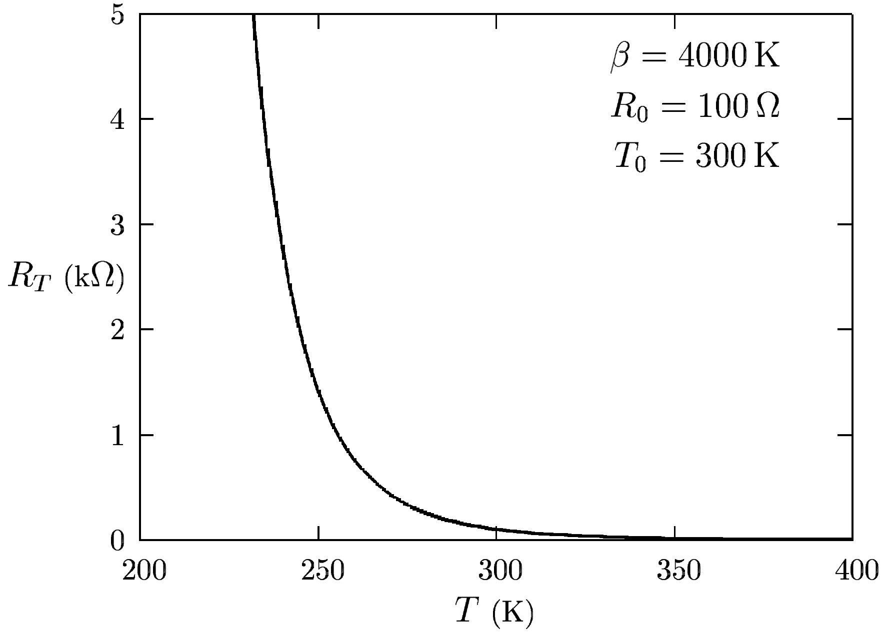


NTC

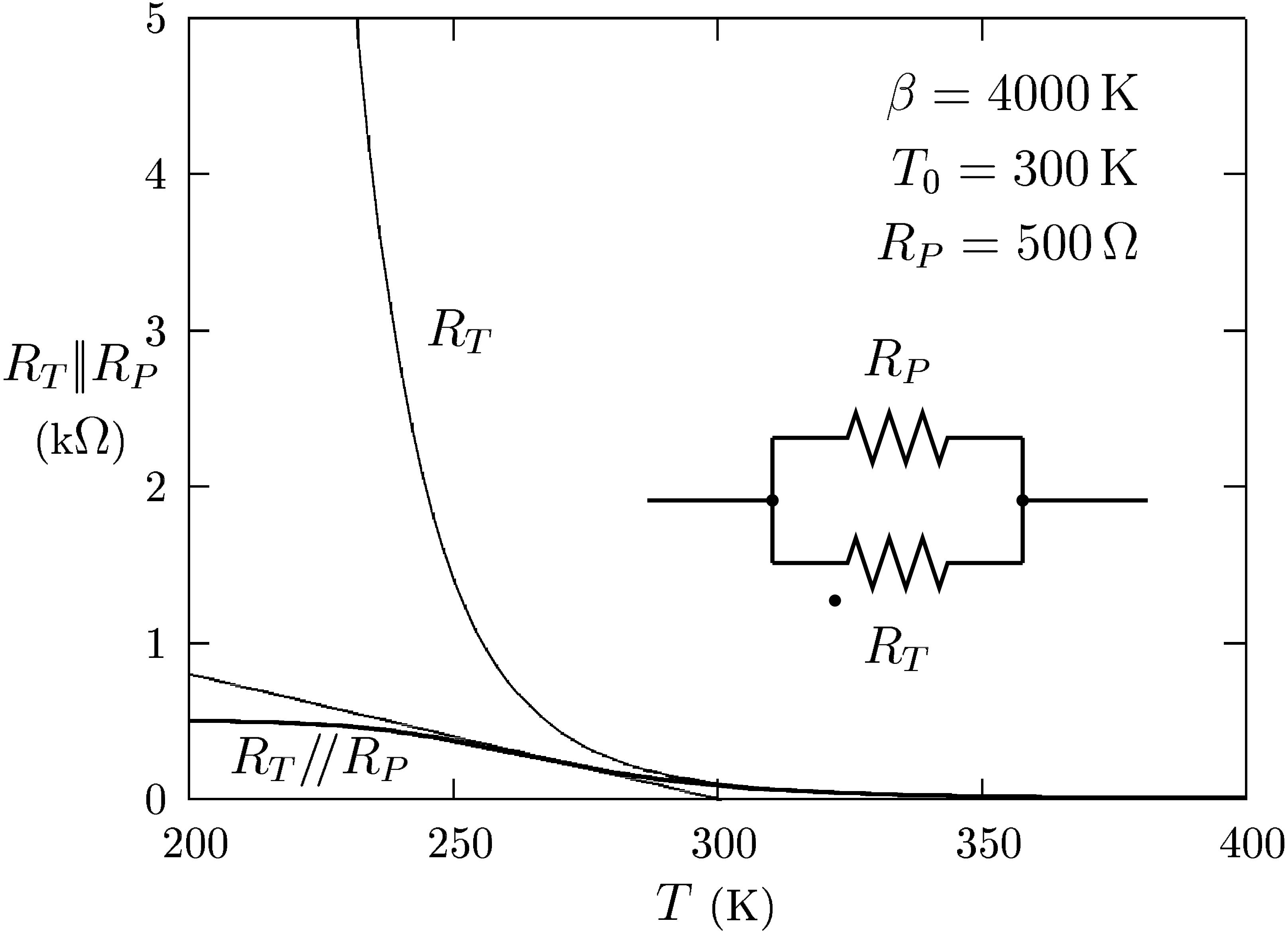
- realizzati con ossidi di Mn, Ni, Co, Cu, Fe, Ti, o con semiconduttori
- fortemente non lineari
- applicazioni in ambito biomedico (flusso respiratorio, temperature, calore di reazione, . . .), facilmente miniaturizzabili.

$$\ln(R) = a_0 + \frac{a_1}{T} \left(+ \frac{a_2}{T^2} + \frac{a_3}{T^3} \right)$$

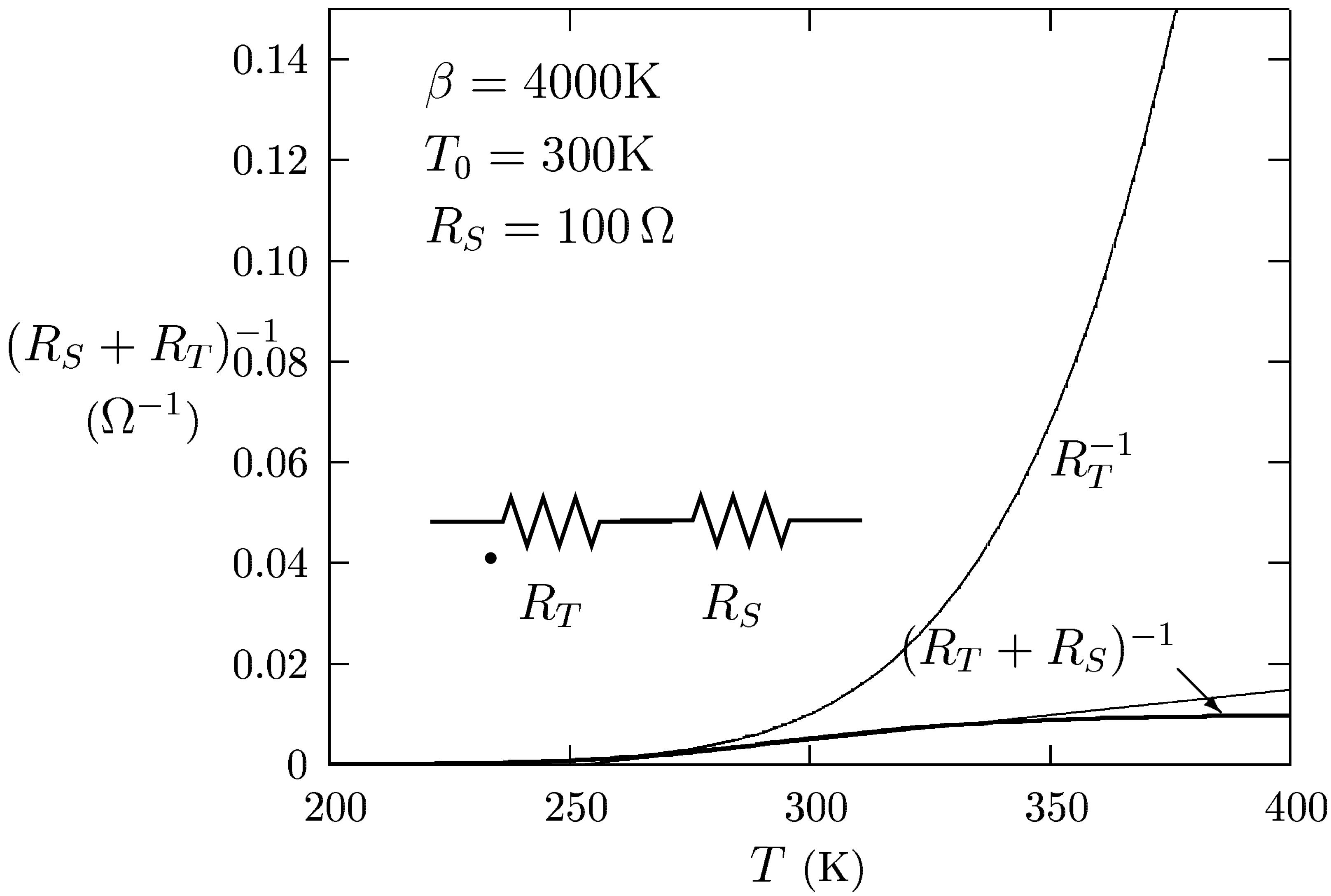
$$R(T) = R_0 \exp \left[\beta \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$



NTC - linearizzazione



NTC - linearizzazione



Sensori integrati di temperatura

Dispositivi a semiconduttore:

- (Possibilità di) integrazione con l'elettronica di pilotaggio/elaborazione:

  riduzione delle dimensioni complessive;

  riduzione dei parametri parassiti (C);

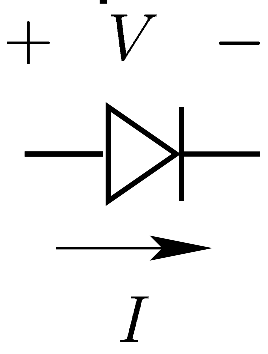
  maggiore affidabilità;

- Sensori basati su (costituiti da) circuiti integrati.

  eventualmente a loro volta integrabili con l'elettronica di pilotaggio/elaborazione.

Sensori di temperatura a semiconduttore

1 - giunzione p-n

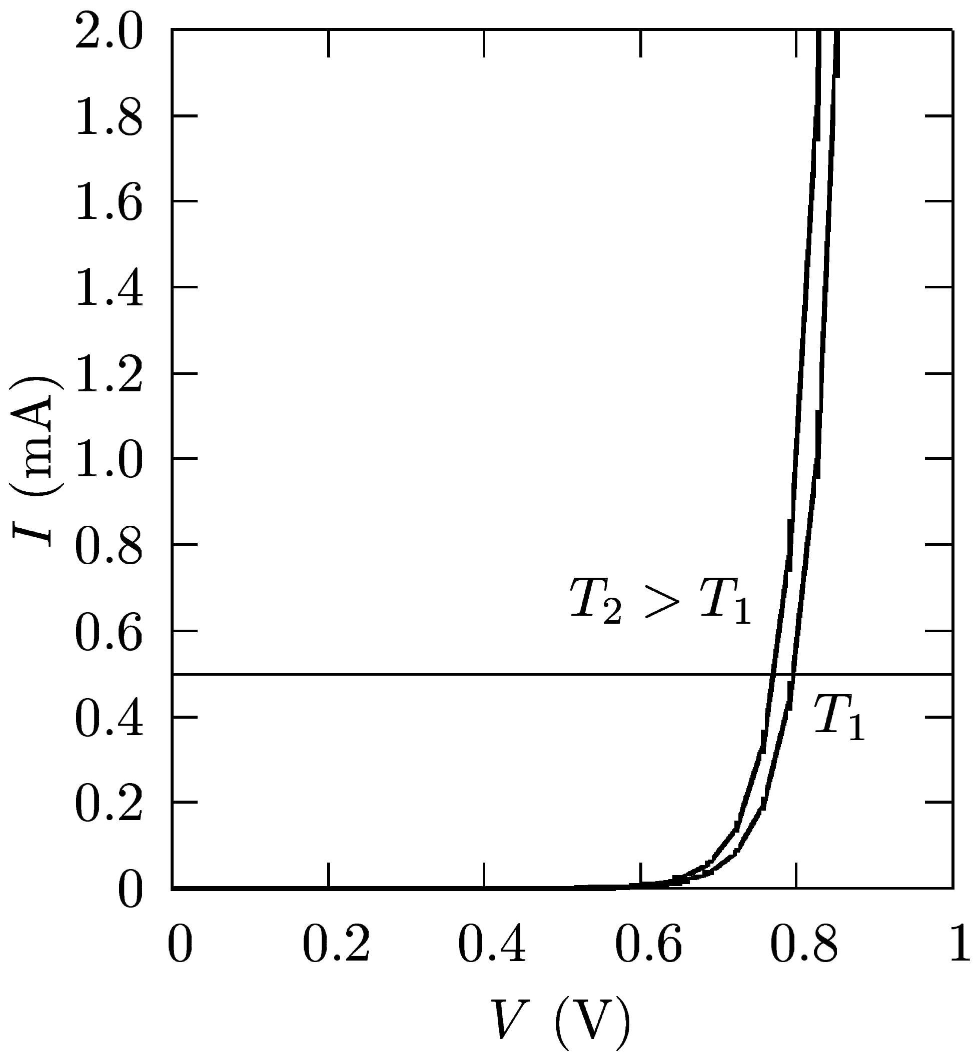


legge della giunzione:

$$I(V) = I_0[\exp(V/\eta V_T) - 1]$$

dipendenza da T:

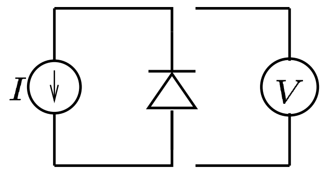
$$\frac{dV}{dT} \simeq -2.5\,\mathrm{mV} \quad (\mathrm{Si},\ I \text{ costante})$$



Curva di calibrazione

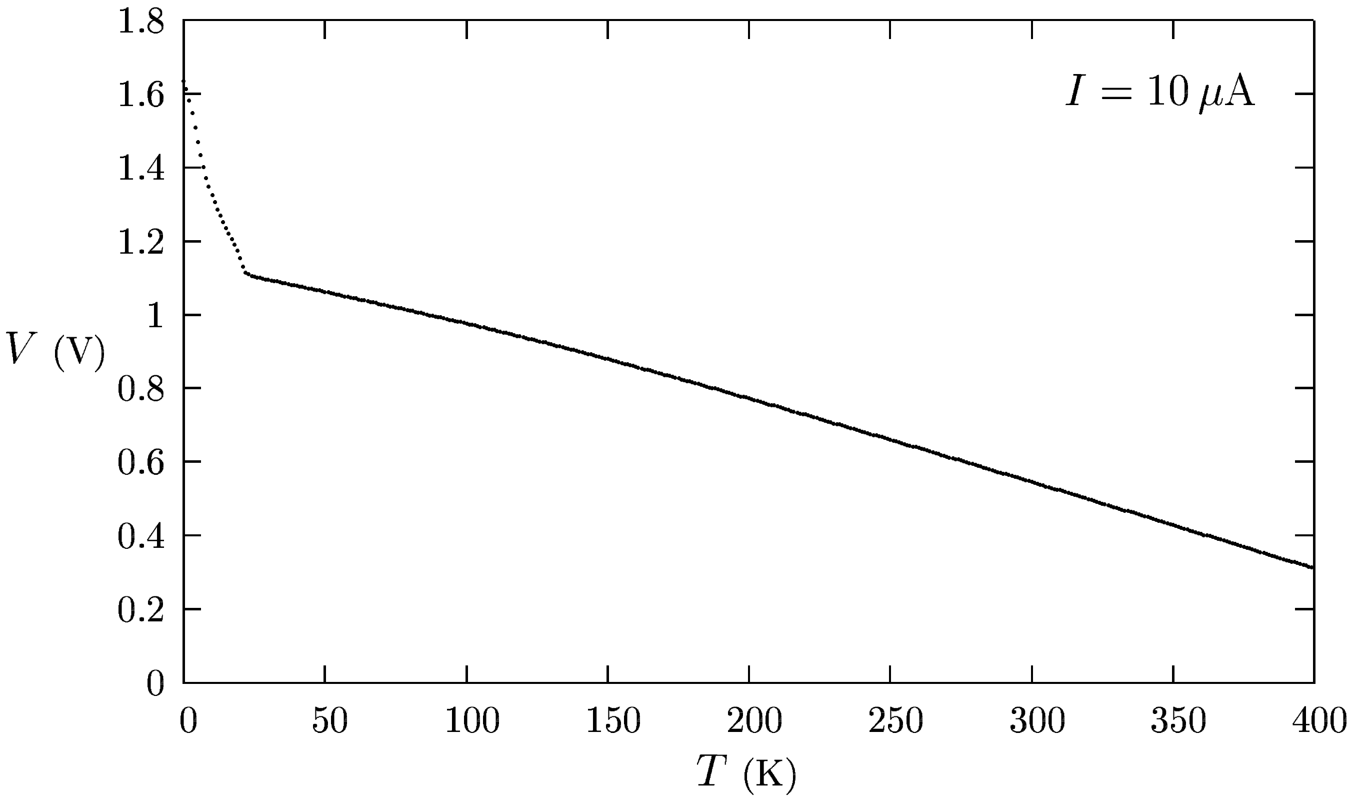
Silicon Diode Thermometer Sensor Model: Si430
Calibration Current: 10 microamps
Typical Response 020-122

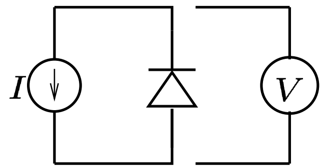
Temp. K	+0.0	+1.0	+2.0	+3.0	+4.0	**+5.0**	+6.0	+7.0	+8.0	+9.0
0		1.64342	1.62255	1.59108	1.55483	1.51590	1.47740	1.44098	1.40827	1.37998
10	1.35568	1.33317	1.31277	1.29401	1.27621	1.25932	1.24342	1.22816	1.21325	1.19816
20	1.18193	1.16246	1.13841	1.12425	1.11828	1.11480	1.11217	1.10996	1.10828	1.10643
30	1.10465	1.10295	1.10124	1.09952	1.09791	1.09629	1.09468	1.09306	1.09145	1.08983
40	1.08821	1.08659	1.08497	1.08334	1.08171	**1.08008**	1.07844	1.07681	1.07517	1.07353
50	1.07188	1.07023	1.06858	1.06693	1.06528	1.06362	1.06196	1.06029	1.05863	1.05696
60	1.05528	1.05360	1.05192	1.05024	1.04856	1.04687	1.04518	1.04349	1.04179	1.04010
320	0.51024	0.50790	0.50556	0.50322	0.50088	0.49854	0.49620	0.49385	0.49151	0.48916
330	0.48681	0.48446	0.48212	0.47977	0.47741	0.47506	0.47271	0.47036	0.46801	0.46565
340	0.46330	0.46095	0.45860	0.45624	0.45389	0.45154	0.44918	0.44683	0.44447	0.44212
350	0.43976	0.43741	0.43505	0.43270	0.43034	0.42799	0.42563	0.42327	0.42092	0.41856
360	0.41620	0.41384	0.41148	0.40913	0.40677	0.40441	0.40205	0.39969	0.39733	0.39497
370	0.39261	0.39025	0.38789	0.38552	0.38316	0.38080	0.37844	0.37607	0.37371	0.37135
380	0.36898	0.36662	0.36425	0.36189	0.35952	0.35715	0.35479	0.35242	0.35005	0.34768
390	0.34532	0.34295	0.34058	0.33821	0.33584	0.33347	0.33109	0.32872	0.32635	0.32398
400	0.32161									



$$V = 1.08008\ \mathrm{V} \quad @45\,\mathrm{K}$$

Sensori di temperatura a semiconduttore

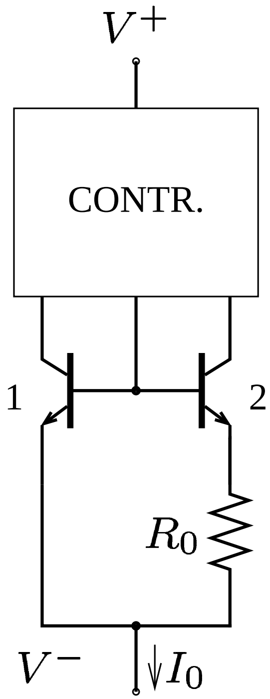




- typical response ($\simeq 250$ EUR);
- dispositivi calibrati ($\simeq 1100$ EUR).

Sensori di temperatura a semiconduttore

2 - sensori a circuiti integrati



$$I_{E1} \simeq I_{C1} \simeq \alpha_{F1} I_{ES1} e^{\dfrac{V_{BE1}}{\eta V_T}}$$

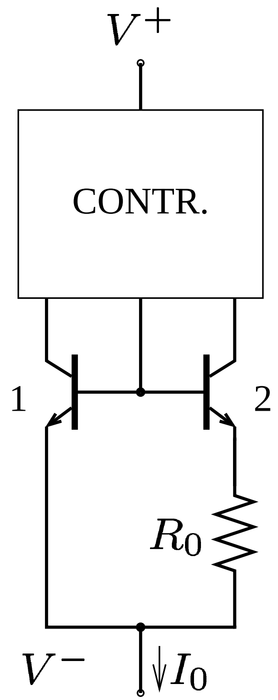
$$I_{E2} \simeq I_{C2} \simeq \alpha_{F2} I_{ES2} e^{\dfrac{V_{BE2}}{\eta V_T}}$$

$$\frac{I_{C1}}{I_{C2}} = 1 = He^{\dfrac{V_{BE1} - V_{BE2}}{\eta V_T}} \qquad \log \frac{1}{H} = \frac{V_{BE1} - V_{BE2}}{\eta V_T}$$

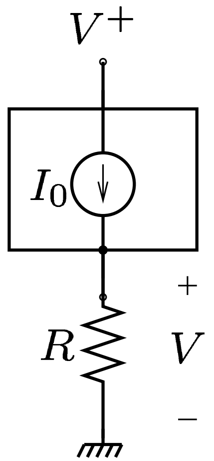
Sensori di temperatura a semiconduttore

$$V_{BE1} - V_{BE2} = \eta V_T \log \frac{1}{H} = \eta \frac{kT}{q} \log \frac{1}{H} \rightarrow V_{BE1} - V_{BE2} \propto T$$

$$V_{BE1} - V_{BE2} \simeq R_0 I_{C2} = 0.5 R_0 (I_{C1} + I_{C2}) = 0.5 R_0 I_0 \propto T$$



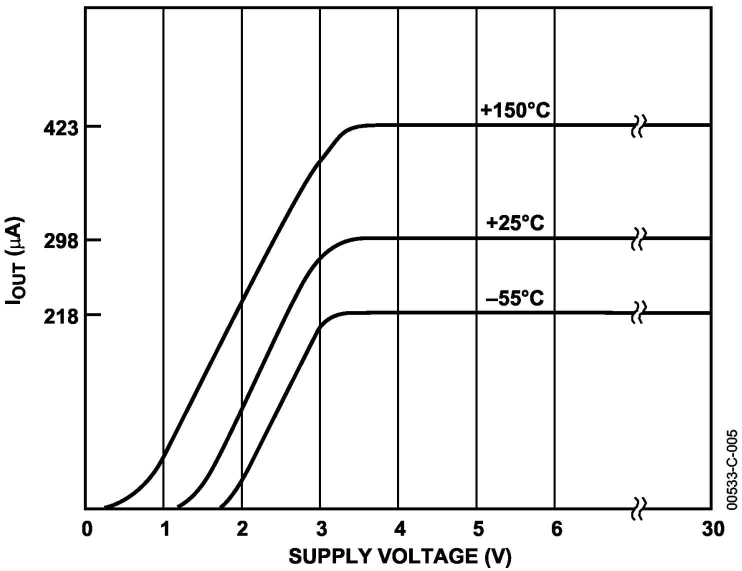
AD590

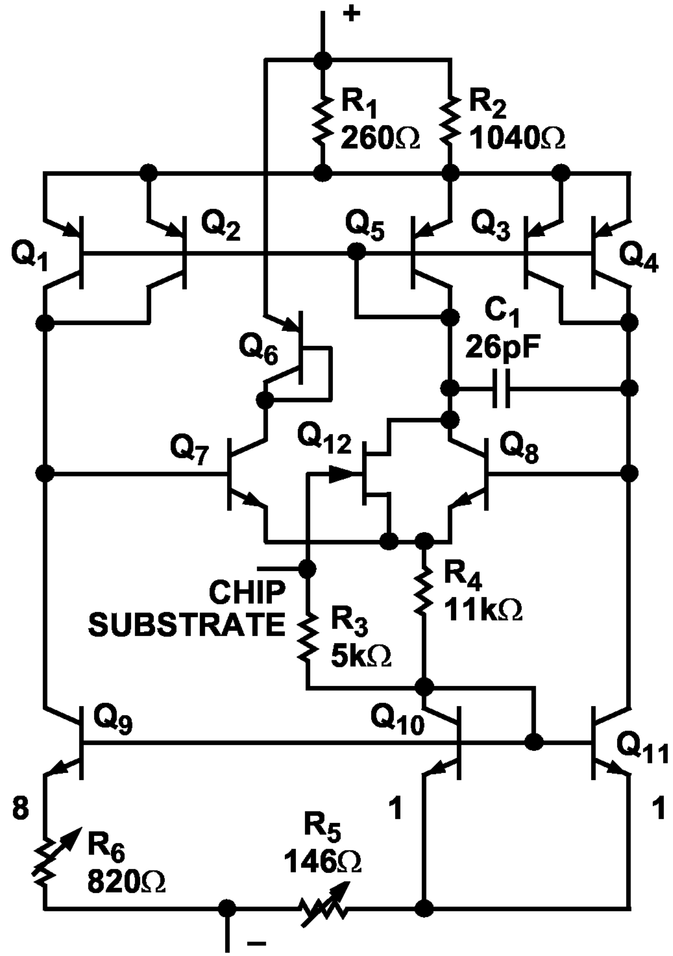


Sensori di temperatura a semiconduttore

AD590:

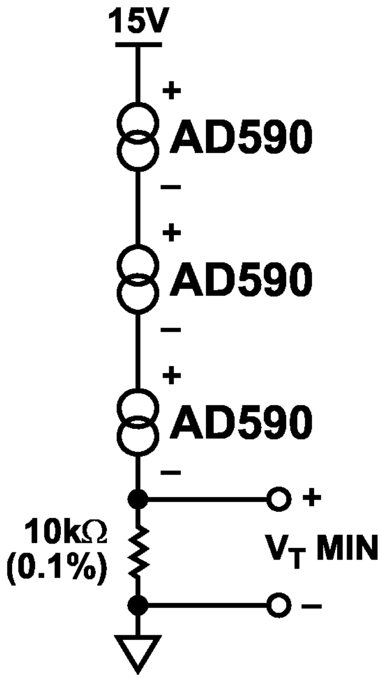
- sens.: $1 \mu \mathrm{A/K}$
- $V^+ : 4 \div 30$ V
- temp. range: $-55 \div 150°\mathrm{C}$

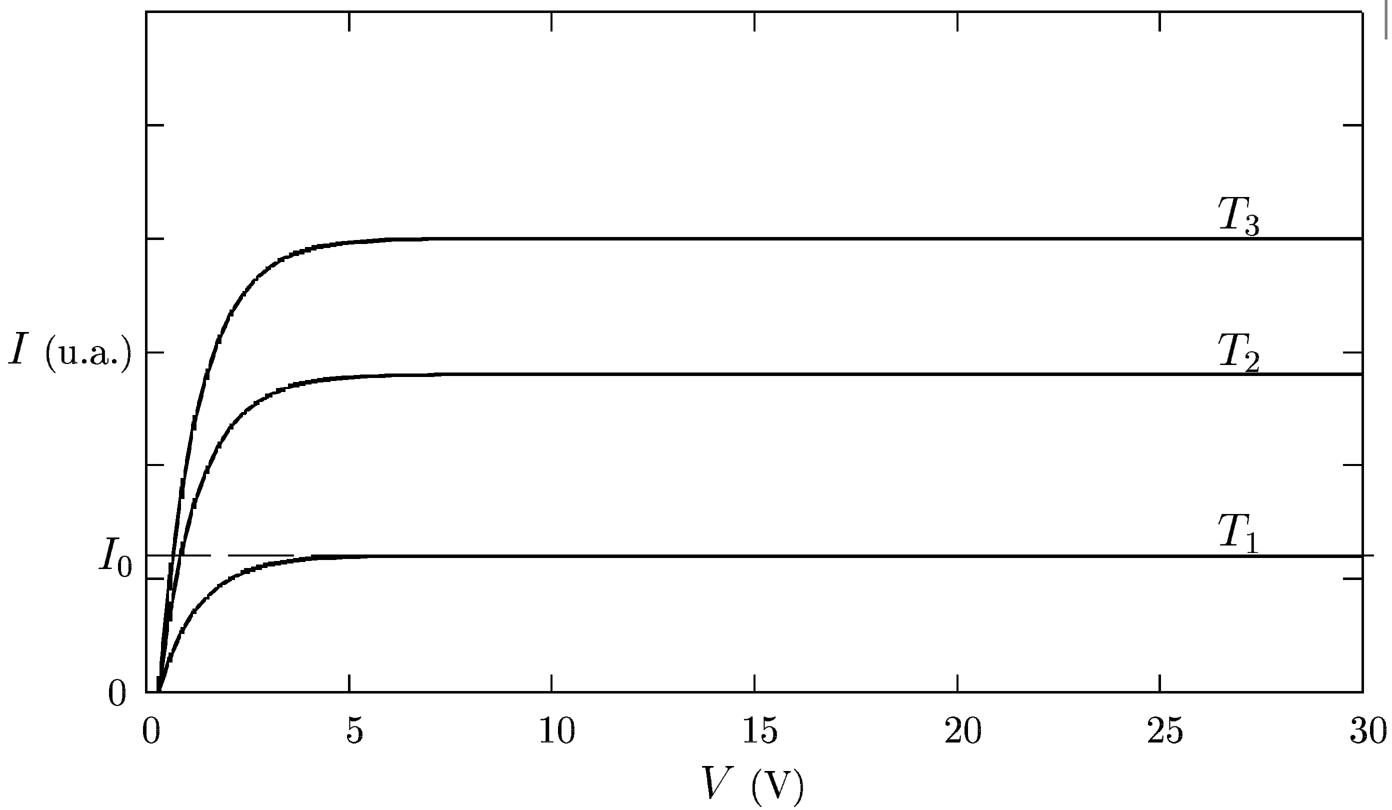




dal sito `http://www.analog.com`

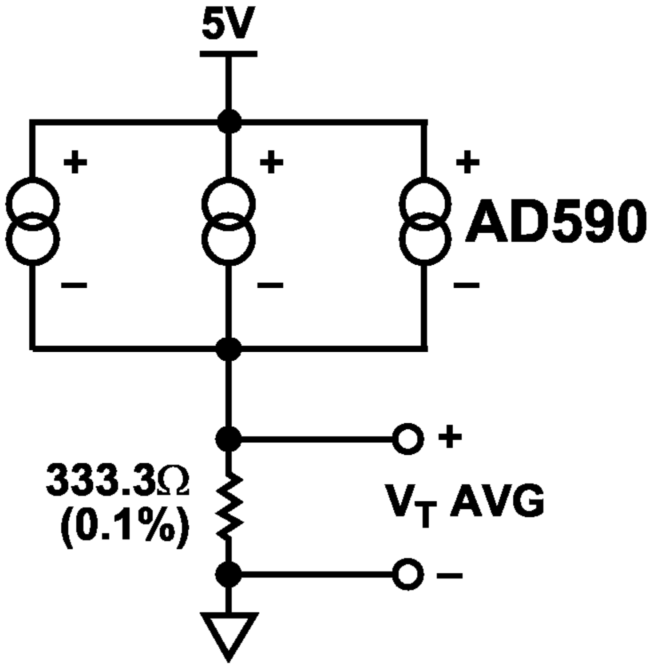
AD590 - esempi di applicazioni (1)





$$V_O \propto \min(T_1, T_2, T_3)$$

AD590 - esempi di applicazioni (2)



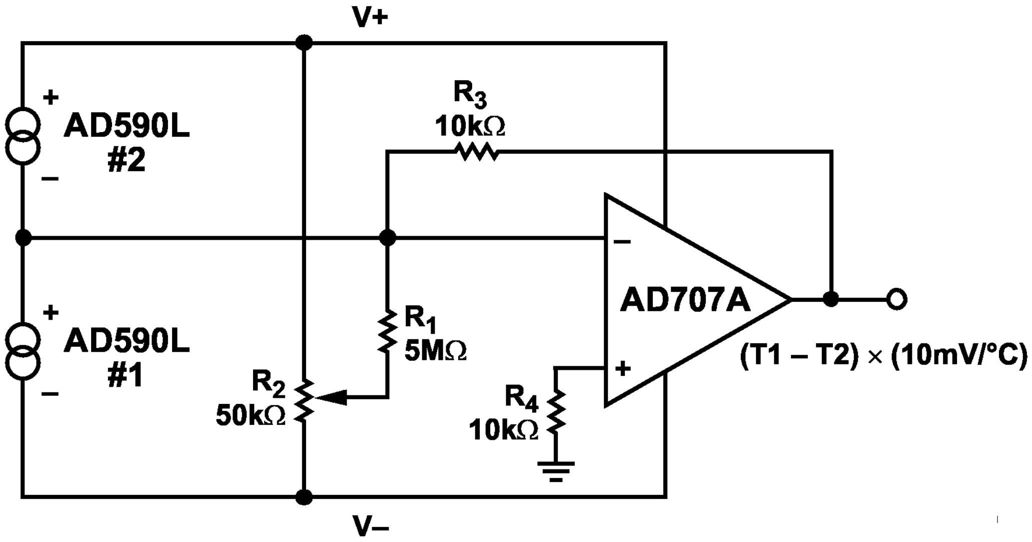
$$V_O = R(I_1+I_2+I_3) = kR(T_1+T_2+T_3)$$

$$V_O = 3kR\frac{T_1+T_2+T_3}{3}$$

$$V_O = k'\frac{T_1+T_2+T_3}{3} \quad (k' = 1\ \mathrm{mV/K})$$

$$V_O \propto \mathrm{med}(T_1, T_2, T_3)$$

AD590 - esempi di applicazioni (3)



$$I_n = kT_n$$

$$k = 1\,\mu\mathrm{A}/\,\mathrm{K}$$

$$V_O = -R_3(I_2 - I_1) = kR_3(T_1 - T_2) \qquad [= 0 \quad \text{se} \quad T_1 = T_2]$$

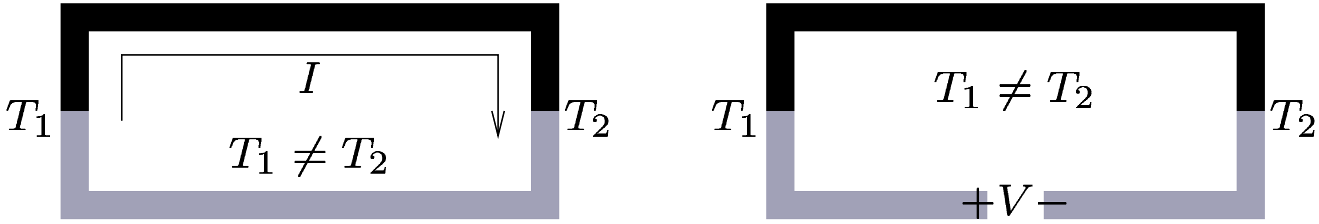
$$V_O = -R_3(I_2 - I_1 + I_{R1}) = kR_3(T_1 - T_2 - T^*), \qquad T^* = I_{R1}/k$$

$$[= 0 \quad \text{se} \quad T_1 - T_2 = T^*]$$

dal sito `http://www.analog.com`

Trasduttori termoelettrici

Effetto Seebek: ($\simeq$ 1820)



t.	mater.	range (°C)	V_{tip}	S
B	Pt/Rh 30% - Pt/Rh 6%	0÷1700	1.24 mV @ 500°C	
E				68 μV/K
J				60 μV/K
K	NiCr - NiAl	-200÷1250	20.64 mV @ 500°C	42 μV/K
	(Cromel - Alumel)			
N				
R	Pt/Rh 13% - Pt	0÷1450	4.47 mV @ 500°C	$\simeq$11 μV/K
T	Cu - CuNi	-200÷350	20.9 mV @ 400°C	
	(Rame - Costantana)			

tipo	composizione		temperature ($^\circ\mathrm{C}$)
B	Pt-30% Rh	Pt-6% Rh	0 $\div$ 1820
E	Ni-Cr	Cu-Ni	-270 $\div$ 1000
J	Fe	Cu-Ni	-210 $\div$ 1200
K	Ni-Cr	Ni-Al	-270 $\div$ 1372
N	Ni-Cr-Si	Ni-Si-Mg	-270 $\div$ 1300
R	Pt-13% Rh	Pt	-50 $\div$ 1768
S	Pt-10% Rh	Pt	-50 $\div$ 1768
T	Cu	Cu-Ni	-270 $\div$ 400

B, R, S: metalli nobili.

Termocoppie

$$E = C_1(T_1 - T_2) + C_2\left(T_1^2 - T_2^2\right) \quad (+\ldots)$$

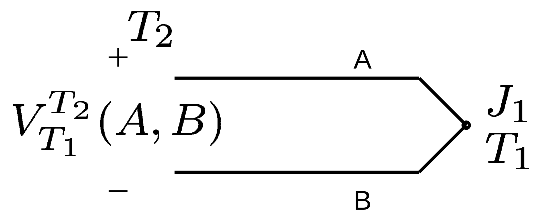
$$E = \sum_{i=1}^{n} C_i T^i \qquad C_i:\ \text{coeff. Seebeck}$$

$$S = \frac{dV}{dT_2} = -C_1 - 2C_2T_2 \quad (T_1 = T_{rif})$$

- caratteristica non lineare

$\rightarrow$ linearizzazione su range ristretto

$\rightarrow$ curva (o tabella) di calibrazione



$T_{rif} = 273\,\mathrm{K}$

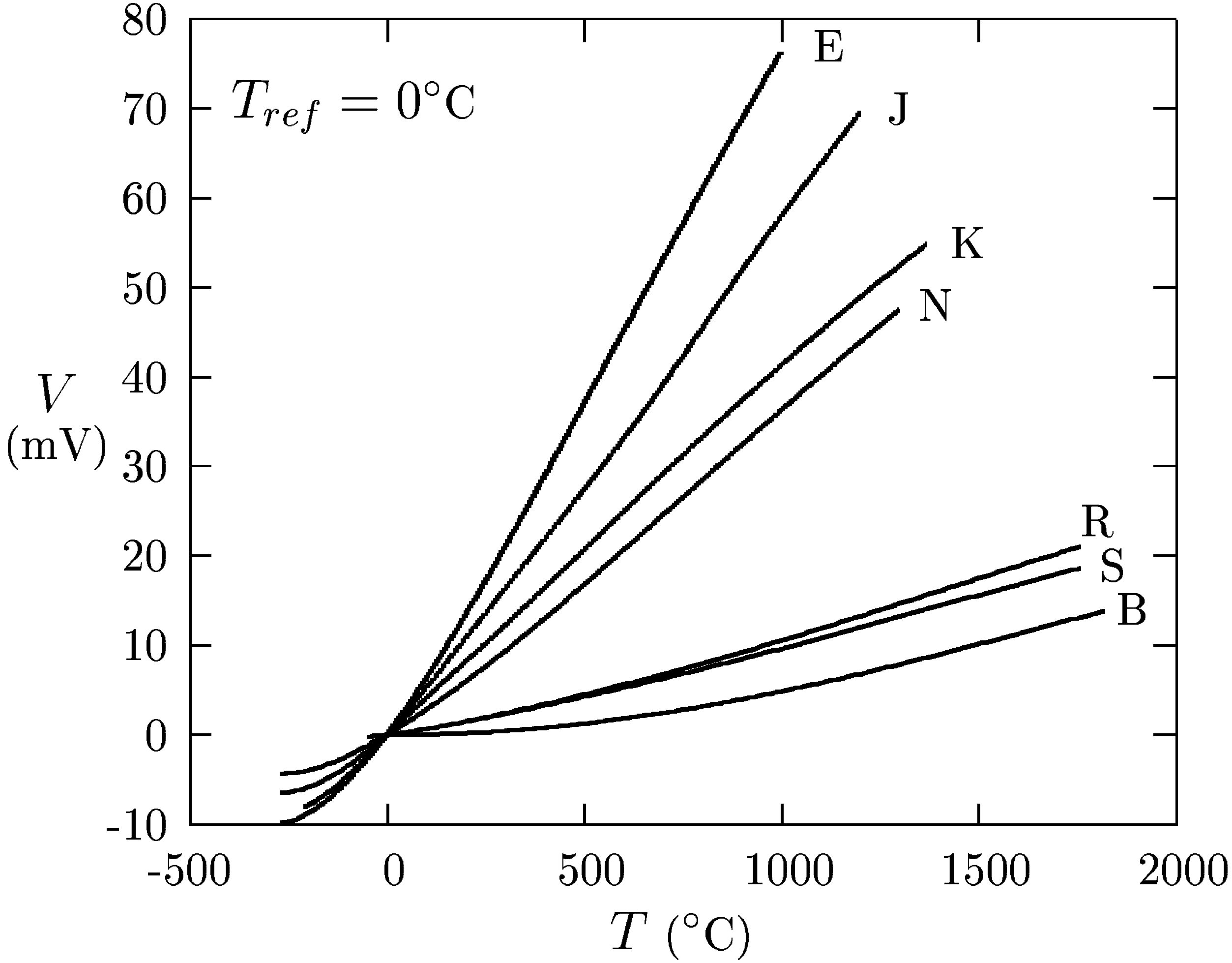
V_A	T_A
V_B	T_B
V_C	T_C
$\ldots$	$\ldots$

$$V_A < V_X < V_B \quad \rightarrow$$

$$T_X = T_A + (T_B - T_A)\frac{V_X - V_A}{V_B - V_A}$$

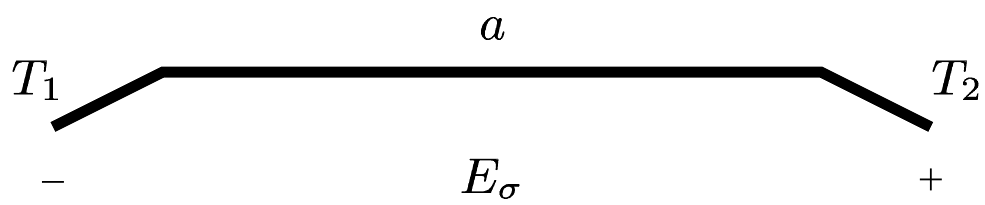
Termocoppie

Caratteristica dipendente dal tipo di termocoppia



fonte: NIST (`http://www.nist.gov`)

Effetto Seebeck - legge fondamentale

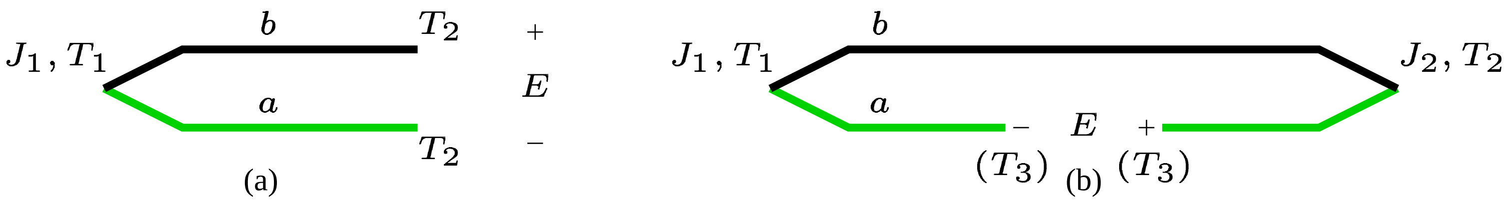


Legge di Seebeck:

$$E_\sigma = \int_{T_1}^{T_2} \sigma_a(T)dT = E_a(T_2) - E_a(T_1)$$

- materiale omogeneo: $\frac{d}{dx}\sigma_a(T) = 0$;
- $\sigma_a(T)$ dipendente dal metallo;
- E_σ indipendente dall'andamento della temperatura lungo il conduttore.

Termocoppia



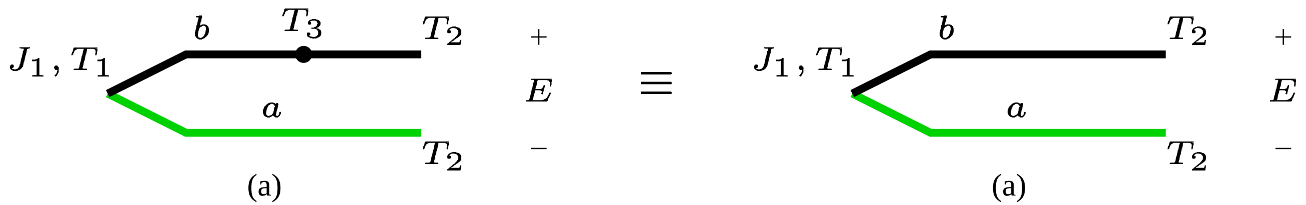
$$E_\sigma = \int_{T_2}^{T_1} \sigma_a(T)dT + \int_{T_1}^{T_2} \sigma_b(T)dT = E_a(T_1) - E_a(T_2) + E_b(T_2) - E_b(T_1)$$

$$E_{T_2}^{T_1}(A, B) \triangleq E_a(T_1) - E_a(T_2) + E_b(T_2) - E_b(T_1)$$

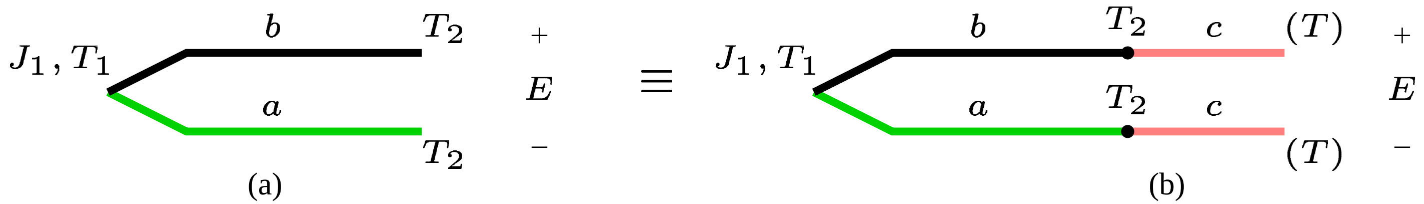
- indifferentemente per (a) o (b)

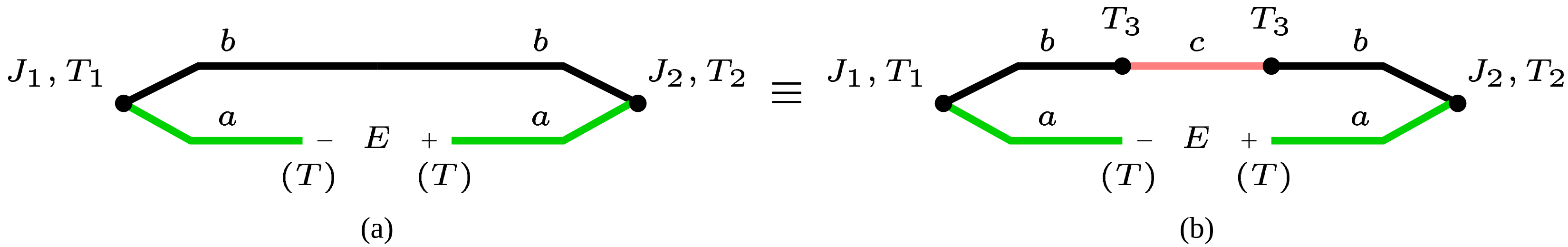
Termocoppie - leggi

- indipendenza dalle temperature intermedie



- legge del terzo metallo

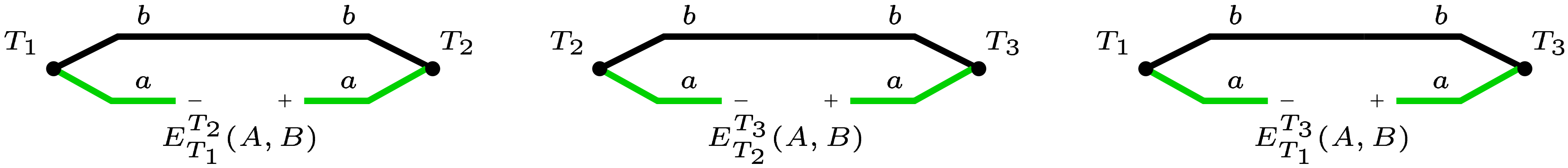




dimostrabile mediante le affermazioni precedenti.

Termocoppie - leggi (2)

- legge della temperatura intermedia

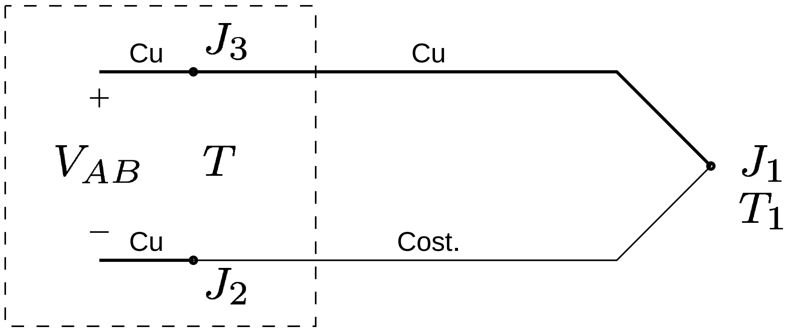


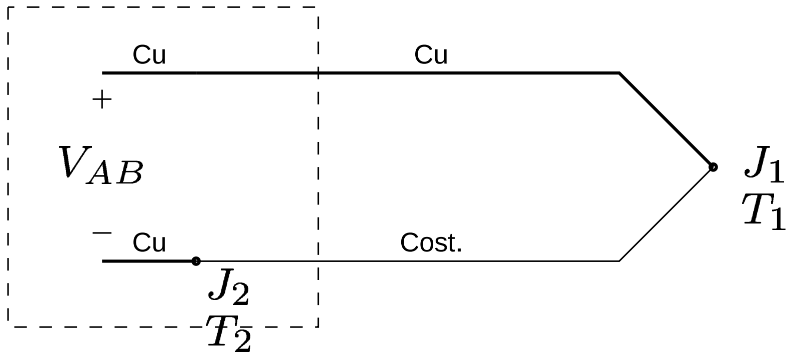
$$E_{T_1}^{T_3}(A,B) = E_{T_1}^{T_2}(A,B) + E_{T_2}^{T_3}(A,B)$$

  - dimostrabile mediante le affermazioni precedenti
  - permette di lavorare con la giunzione fredda a temperatura qualsiasi, purché nota (compensazione)

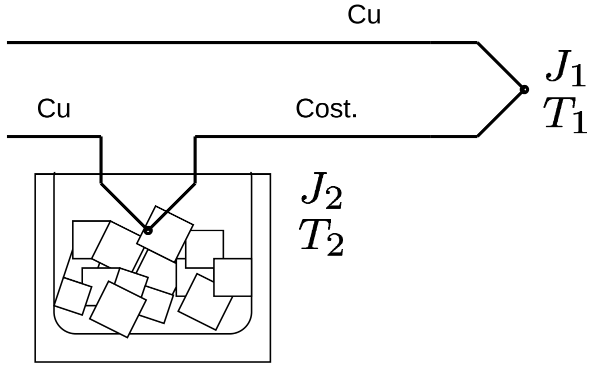
Termocoppie - misura

a) $B \neq A = \mathrm{Cu}$



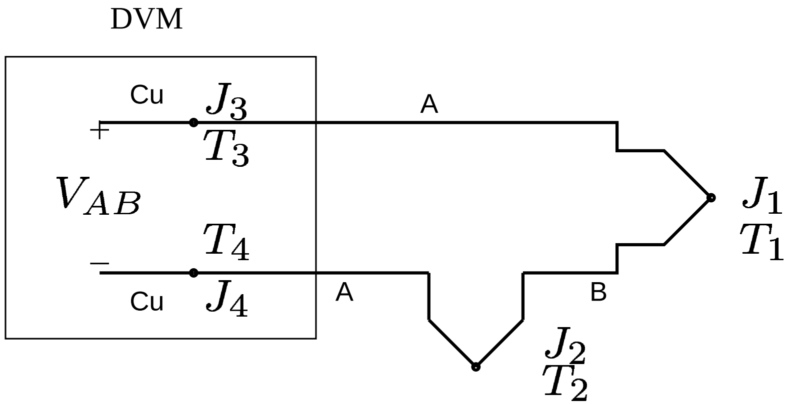


T_2 deve essere nota $\rightarrow$ bagno termostatico



Termocoppie - misura

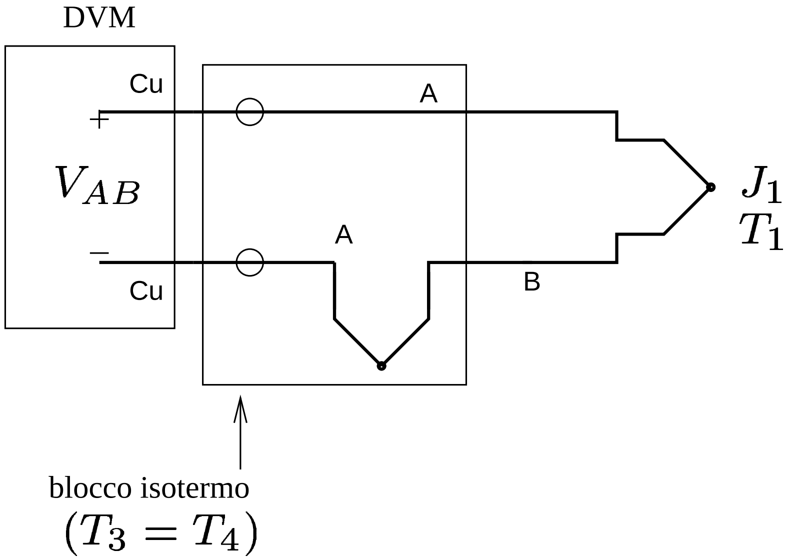
b) $A \neq B \neq \mathrm{Cu}$

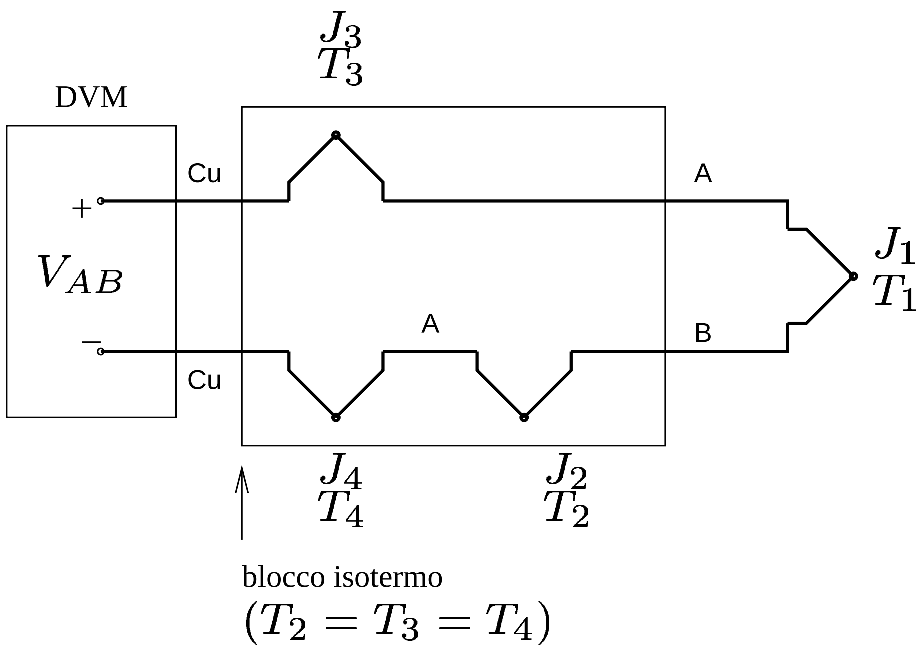


$T_3 = T_4$?

Termocoppie - misura

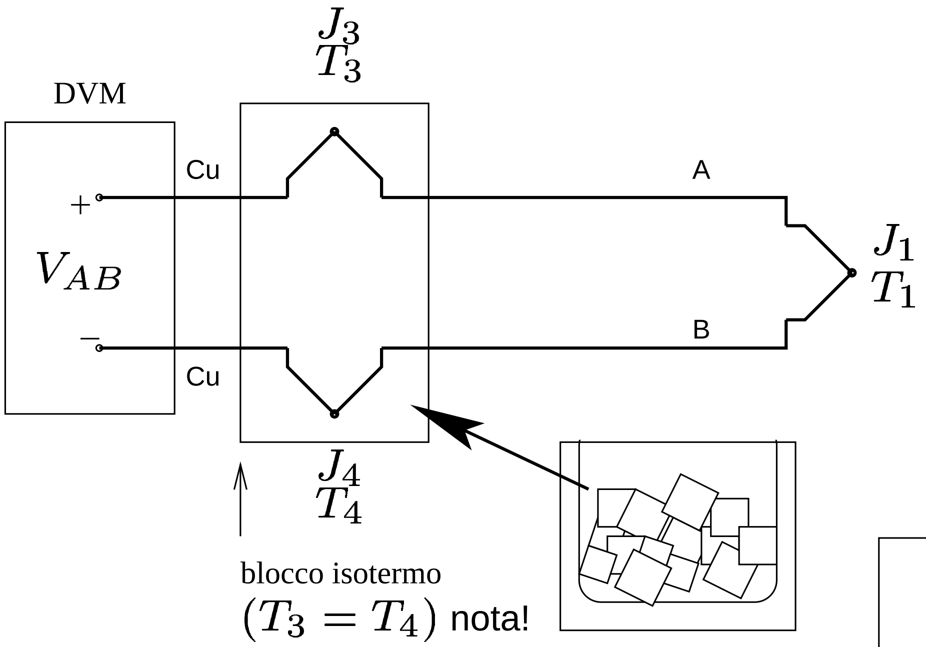
b) $A \neq B \neq \mathrm{Cu}$ (cont.)

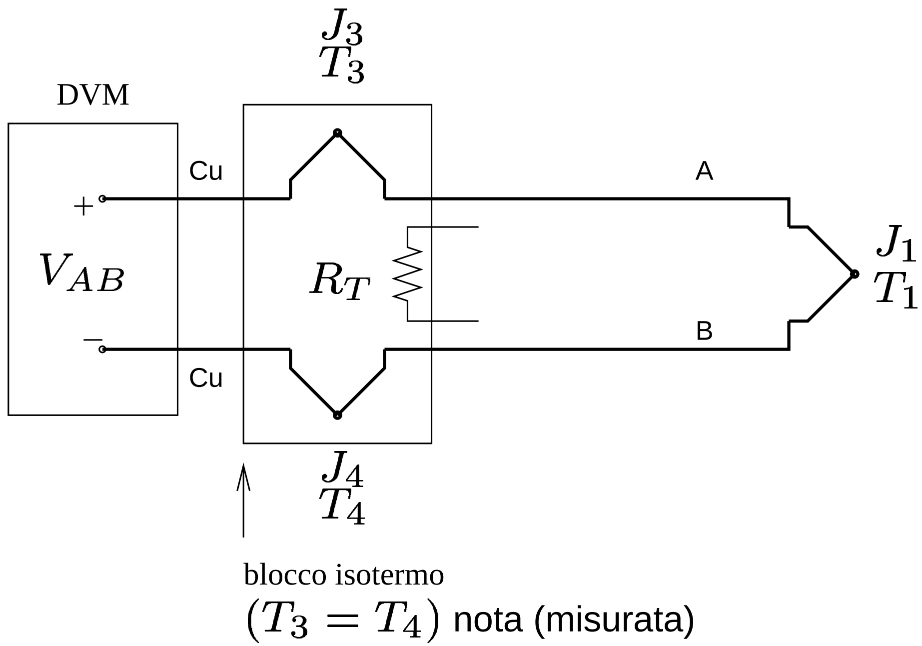




Termocoppie - misura

b) $A \neq B \neq \mathrm{Cu}$ (cont.)





Termocoppie

Realizzazione:

- fili saldati alle estremità
- deposizione dei metalli su substrato

Altre caratteristiche:

- intervallo di misura: $-100°\mathrm{C} \div 2300°\mathrm{C}$
- dipendenza delle caratteristiche da impurezze (calibrazione)
- necessità di amplificazione della tensione
- necessità di riferimento di temperatura
- discreta robustezza (sonda / termocoppia esposta)

Termocoppie *

- possibilità di impiego in ambienti aggressivi
- possibilità di impiego per alte temperature
- bassa sensibilità a basse temperature
- dimensioni molto ridotte

  $\rightarrow$ impieghi anche in aghi e cateteri
- tempo di risposta (transistorio termico): $\mathrm{ms} \div \mathrm{s}$ (dipende dalle modalità costruttive, isolamento termico).

Termocoppie

ISE, Inc.

ITS-90 Table for Type B Thermocouple (Ref Junction 0°C)

Thermoelectric Voltage in mV

B

°C	0	1	2		7	8	9	10
100	0.033	0.034	0.035		0.040	0.041	0.042	0.043
110	0.043	0.044	0.045		0.050	0.051	0.052	0.053
120	0.053	0.055	0.056	. . .	0.062	0.063	0.064	0.065
130	0.065	0.066	0.068		0.074	0.075	0.077	0.078
140	0.078	0.079	0.081		0.088	0.089	0.091	0.092

dal sito `http://iseinc.com`

Termocoppie

appr. polinomiale: $E = \sum_{i=0}^{n} c_i T^i, \quad [E] = \text{ mV}, [T] =^{\circ} \text{C}$

```
range:  0.000 ÷ 630.615, n=6
 0.000000000000E+00
-0.246508183460E-03
 0.590404211710E-05
-0.132579316360E-08
 0.156682919010E-11
-0.169445292400E-14
 0.629903470940E-18

range:  630.615 ÷ 1820.000, n=8
-0.389381686210E+01
 0.285717474700E-01
   ...
```

tipo B, fonte: NIST (`http://www.nist.gov`)

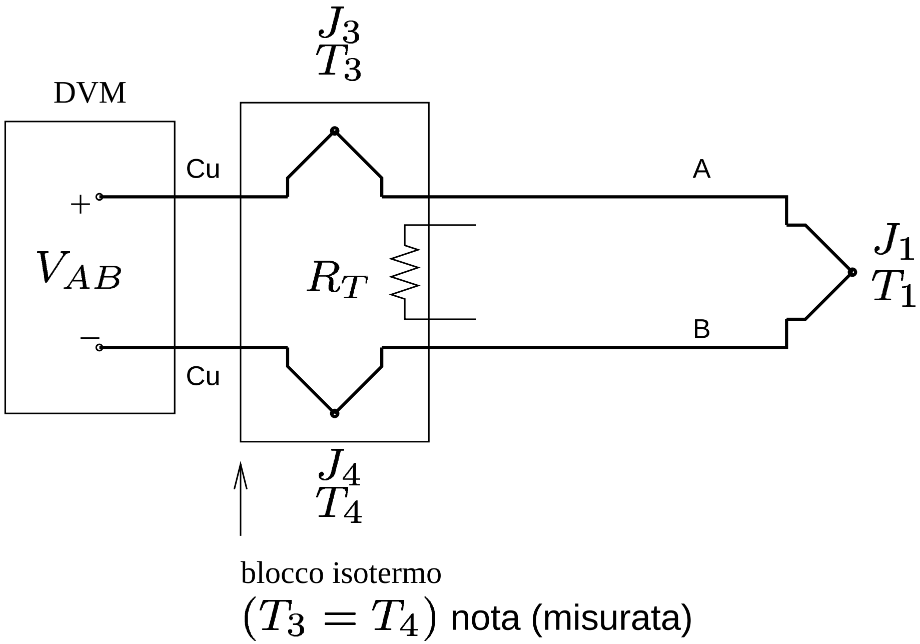
Termocoppie

appr. polinomiale: $T = \sum_{i=0}^{n} d_i E^i, \quad [E] = \text{ mV}, [T] =^\circ \text{C}$

```
Inverse coefficients for type B:

Temperature   250.             700.
  Range:      700.            1820.

  Voltage    0.291            2.431
  Range:     2.431           13.820

       9.8423321E+01  2.1315071E+02
       6.9971500E+02  2.8510504E+02
      -8.4765304E+02 -5.2742887E+01
       1.0052644E+03  9.9160804E+00
      -8.3345952E+02 -1.2965303E+00
       4.5508542E+02  1.1195870E-01
      -1.5523037E+02 -6.0625199E-03
       2.9886750E+01  1.8661696E-04
      -2.4742860E+00 -2.4878585E-06
```

fonte: NIST (`http://www.nist.gov`)

Termocoppie - misure



$$V_{AB} = V_{T_1}^{T_3}(A, B)$$

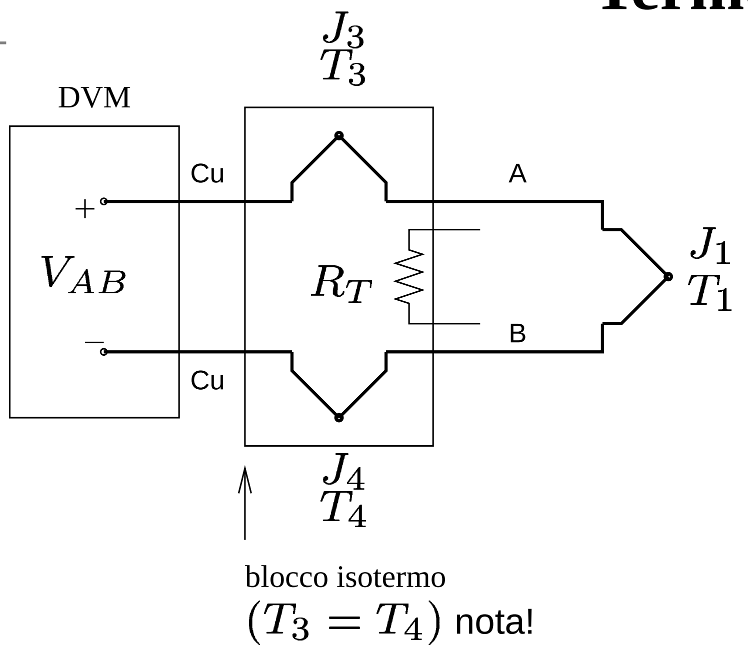
(l. del metallo intermedio)

Effetti della terza temperatura:

$$V_{T_1}^{T_3}(A, B) = V_{T_0}^{T_3}(A, B) + V_{T_1}^{T_0}(A, B)$$

T_0 qualsiasi

Termocoppie - misure



$$V_{T_1}^{T_3}(A,B) = V_{T_0}^{T_3}(A,B) + V_{T_1}^{T_0}(A,B)$$

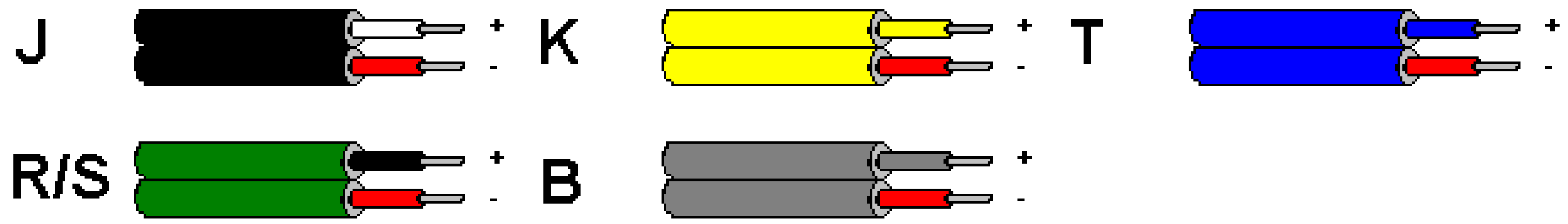
$$T_0 = 0^\circ\mathrm{C}, T_3 \;\; \text{nota}$$

- misura di V_{AB}
- misura di T_3
- determinazione di $V_{T_0}^{T_3}(A,B)$ (da tabelle)
- calcolo di $V_{T_1}^{T_0}(A,B)$ (differenza, compensazione)
- determinazione di T_1 (da tabelle)

Termocoppie

codice a colori:

United States ASTM:



German DIN: