Sensori meccanici

Caratterizzazione dei sensori meccanici:

- tipi di dispositivi, circuito di lettura (read-out) e modello del sensore (sensibilità)

1. Sensori piezoelettrici:

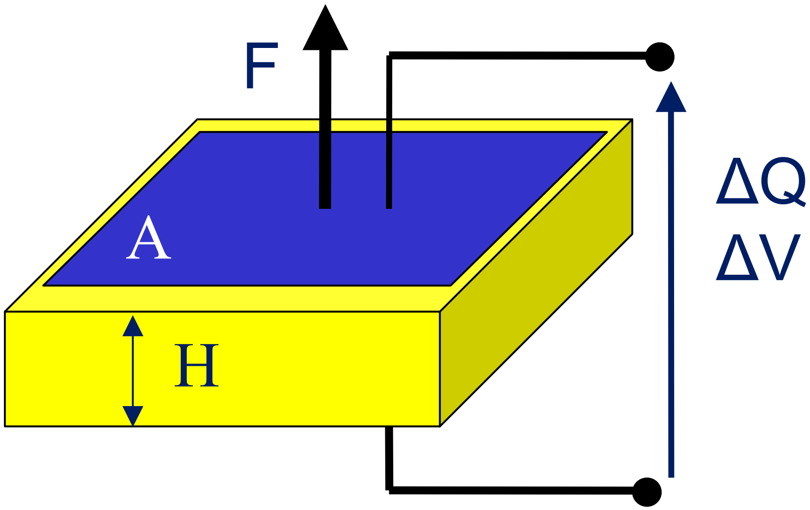
   1.1 sensore di accelerazione PI-FET (Chen et al., 1980)

2. Sensori piezoresistivi:

   2.1 sensore di pressione ad alta precisione per applicazioni biomediche (Samaun et al., 1973)

   2.2 sensore MAP (MOTOROLA)

Sensori piezoelettrici



$$\Delta Q = DA = d\sigma A = dF$$

$$\Delta V = \frac{dF}{\varepsilon A/H} = \frac{dH\sigma}{\varepsilon}$$

$$D_i = \varepsilon_{ik} E_k + d_{i,kl} \sigma_{kl}$$

Sensori piezoelettrici

$$D_i = \varepsilon_{ik} E_k + d_{i,kl} \sigma_{kl}$$

$$\varepsilon = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

	$\varepsilon_{11} = \varepsilon_{22}$	ε_{33}
SiO_2	$4.5\ \varepsilon_0$	$4.6\ \varepsilon_0$
$BaTiO_3$	$1268\ \varepsilon_0$	$1419\ \varepsilon_0$
ZnO	$10.8\text{-}11\ \varepsilon_0$	$10.8\text{-}11\ \varepsilon_0$

Sensori piezoelettrici

$$D_i = \varepsilon_{ik} E_k + d_{i,kl} \sigma_{kl}$$

σ_{kl} ⇒ σ_m , $m = 1,\ldots,6$ ⇒ $d_{i,kl}$ ⇒ d_{im}

$$\boldsymbol{d} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix}$$

Sensori piezoelettrici

$$\mathbf{d} = \begin{bmatrix} d_{11} & d_{11} & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & -2\,d_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{d} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}$$

SiO_2

d_{11} = – 2.31 pC/N

d_{14} = – 0.727 pC/N

$BaTiO_3$

d_{31} = – 79 pC/N

d_{33} = 191 pC/N

d_{15} = 270 pC/N

ZnO

d_{31} = – 5.1 pC/N

d_{33} = 12.3 pC/N

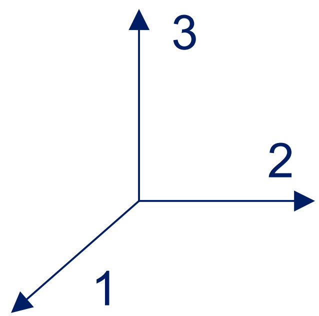
d_{15} = -8.3 pC/N

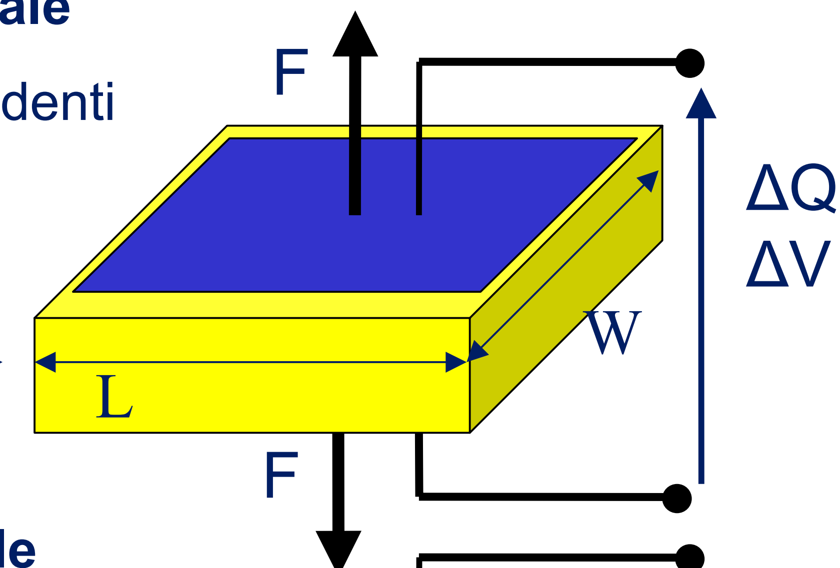
Sensori piezoelettrici

Coefficiente piezoelettrico longitudinale

Es. ZnO con assi caratteristici corrispondenti agli assi indicati in figura:

$D_3 = d_{33}$ F/(WL)

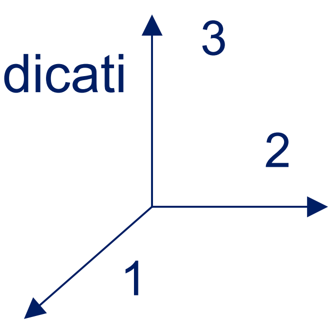


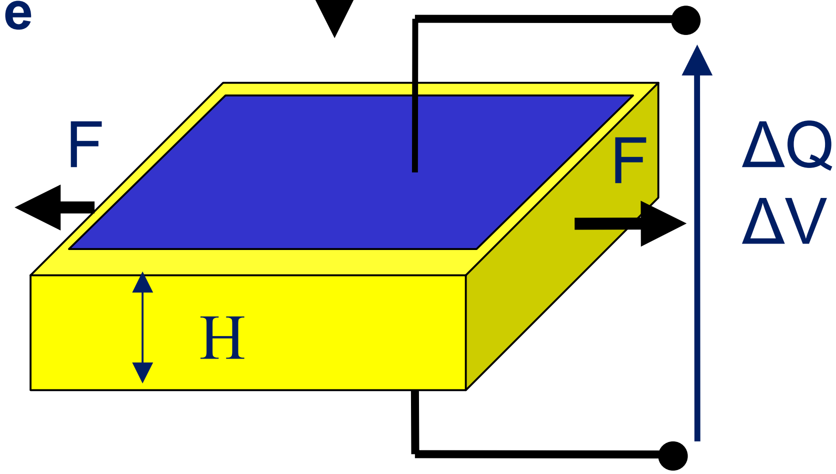


Coefficiente piezoelettrico trasversale

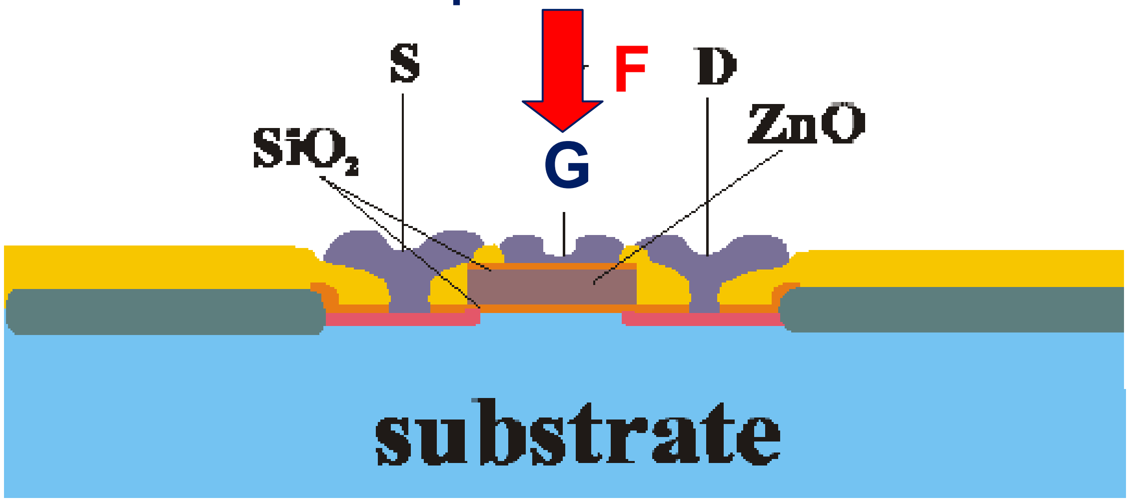
Es. ZnO con assi caratteristici corrispondenti agli assi indicati in figura:

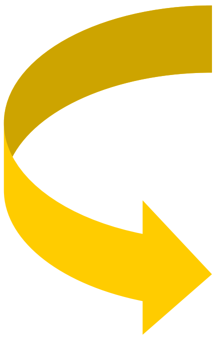
$D_3 = d_{31}$ F/(HW)

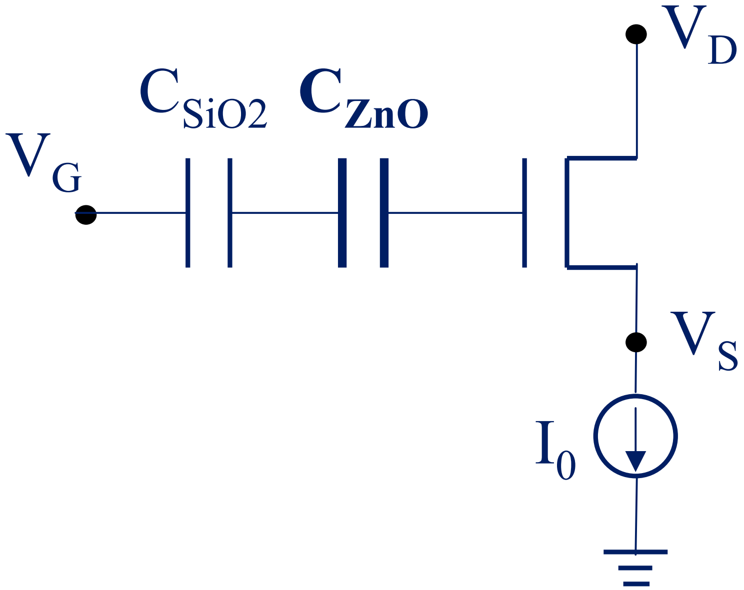




Sensori piezoelettrici

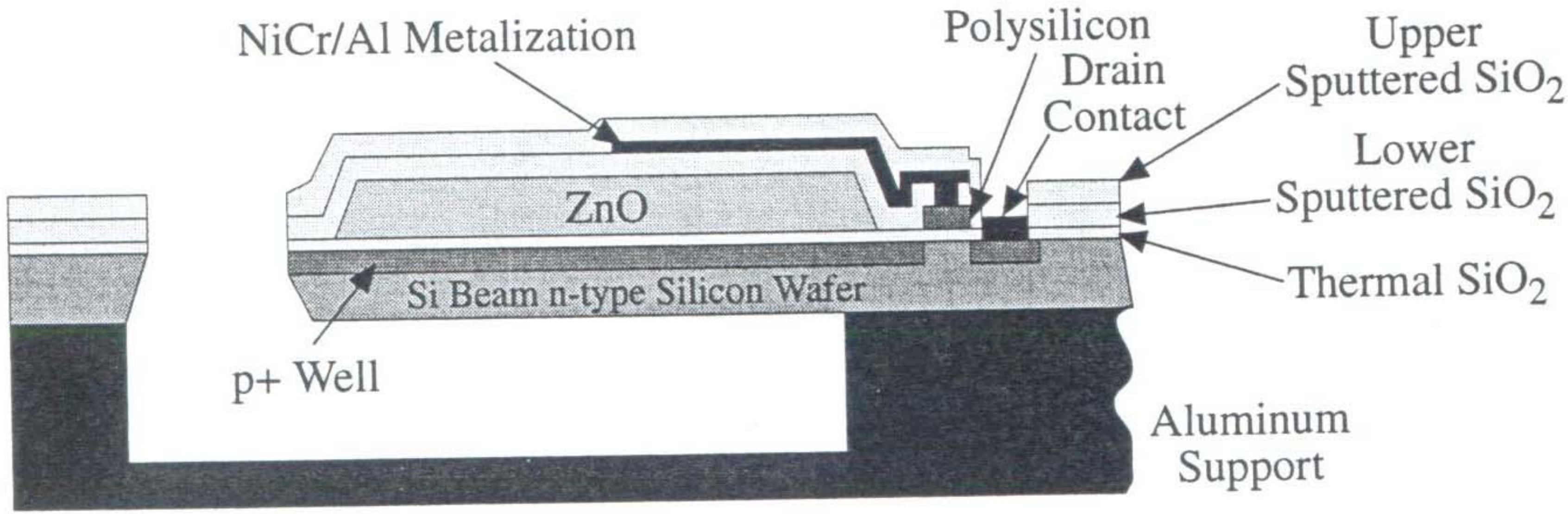






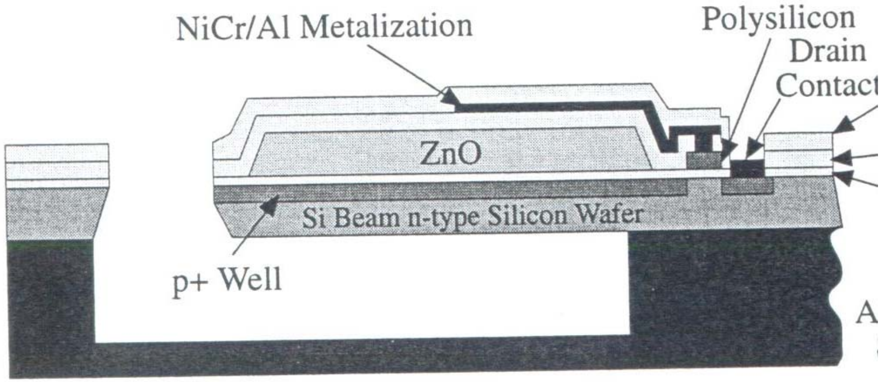
Sensore di accelerazione piezoelettrico PI-FET

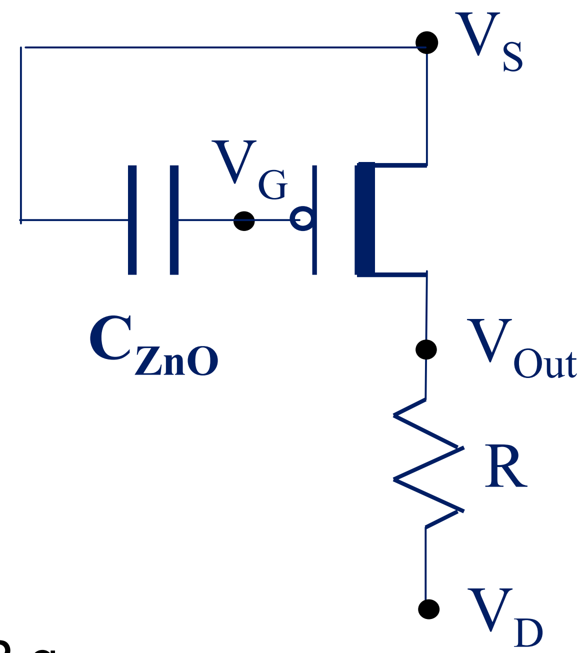
(P. Chen et al., “Integrated silicon microbeam PI-FET accelerometer”, IEEE Tr. ED 29, 1982)



Analisi del circuito di lettura:

1. Amplificatore a uno stadio (pFET a svuotamento)

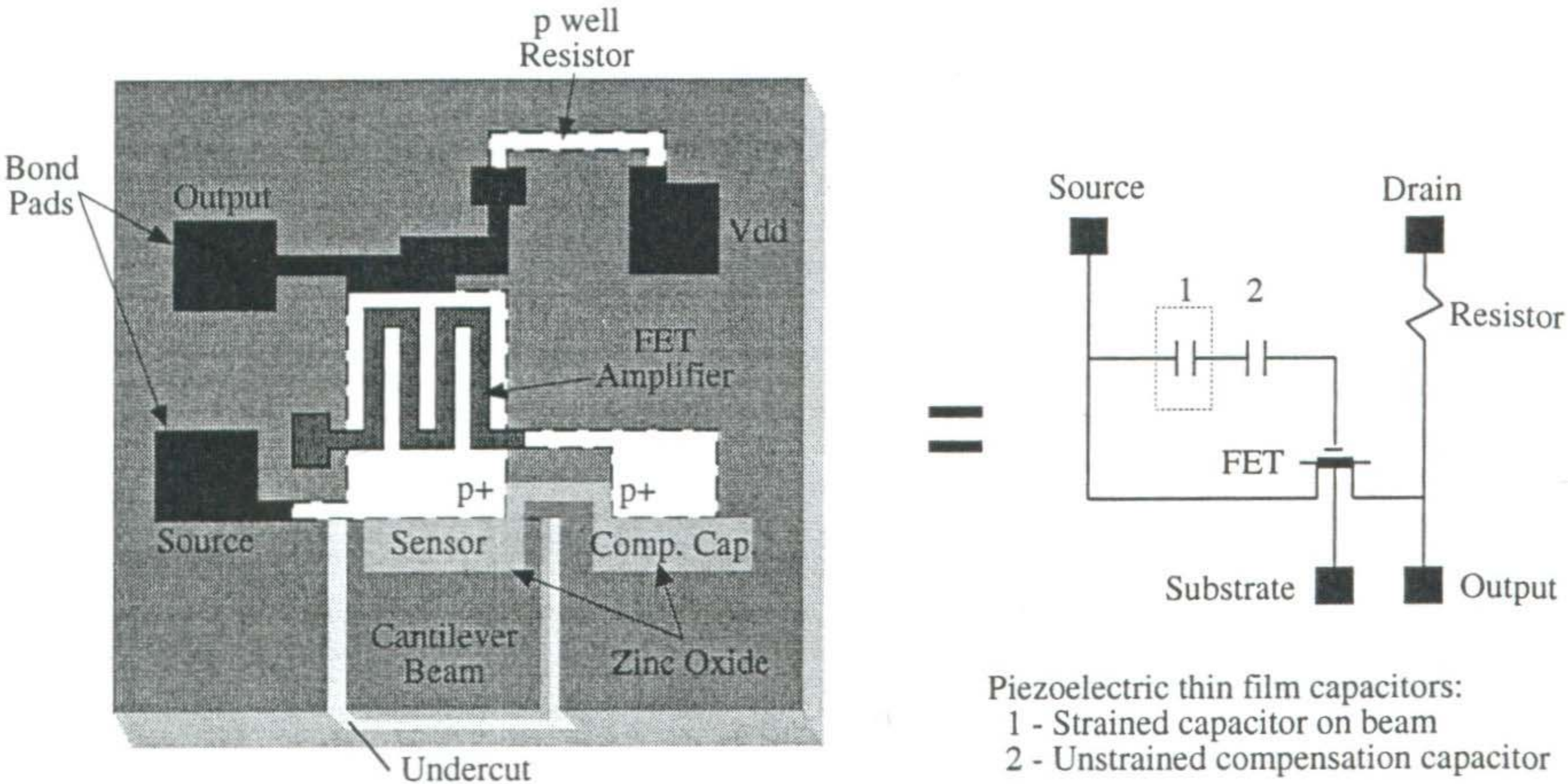


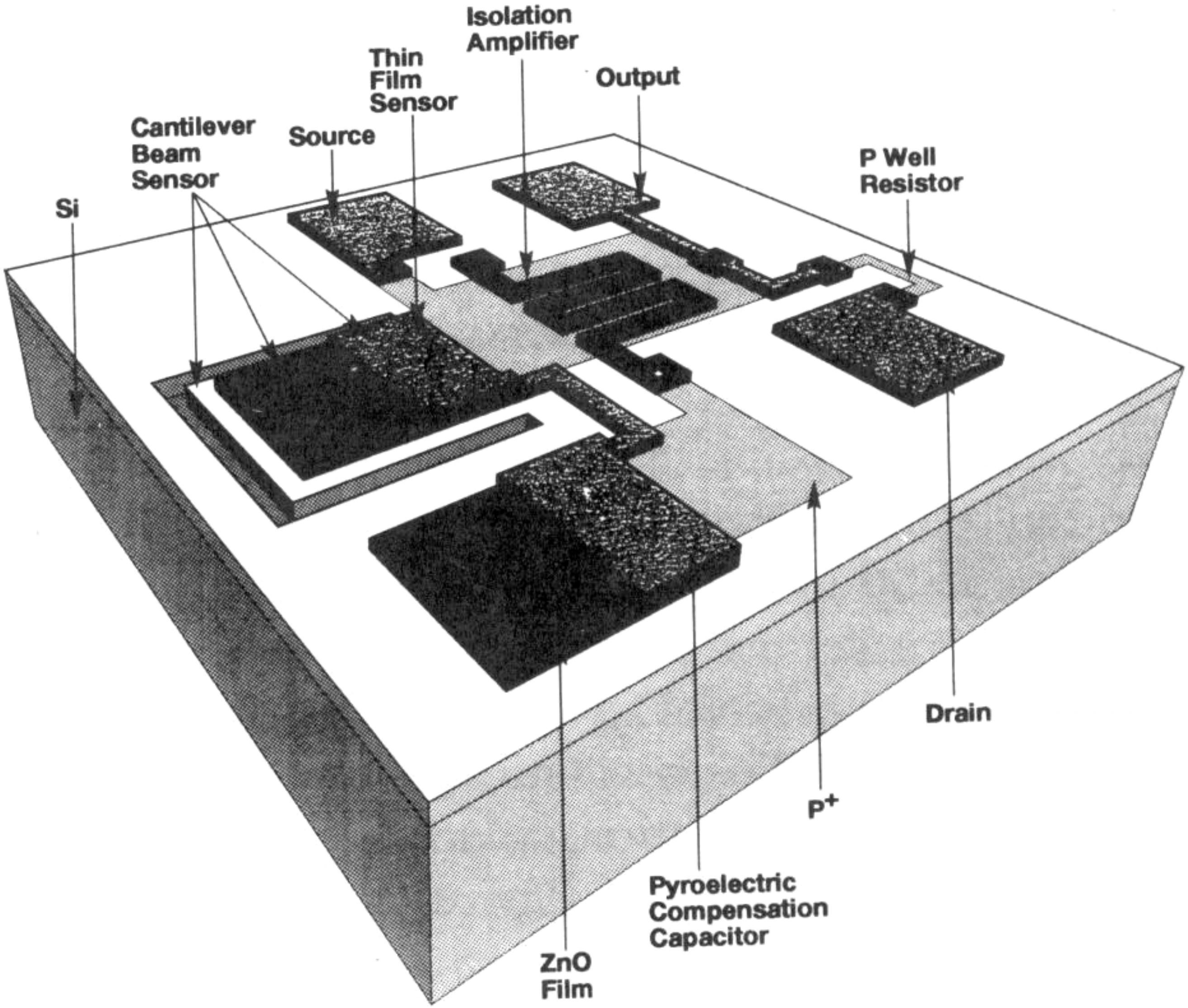


guadagno di tensione dell’amplificatore: $A_v = -R\ g_{mp}$

Analisi del circuito di lettura:

2. Circuito di compensazione delle variazioni dovute alla temperatura




Isolation Amplifier
Output
Thin Film Sensor
Cantilever Beam Sensor
Source
P Well Resistor
Si
Drain
P^+
Pyroelectric Compensation Capacitor
ZnO Film

Sensori meccanici

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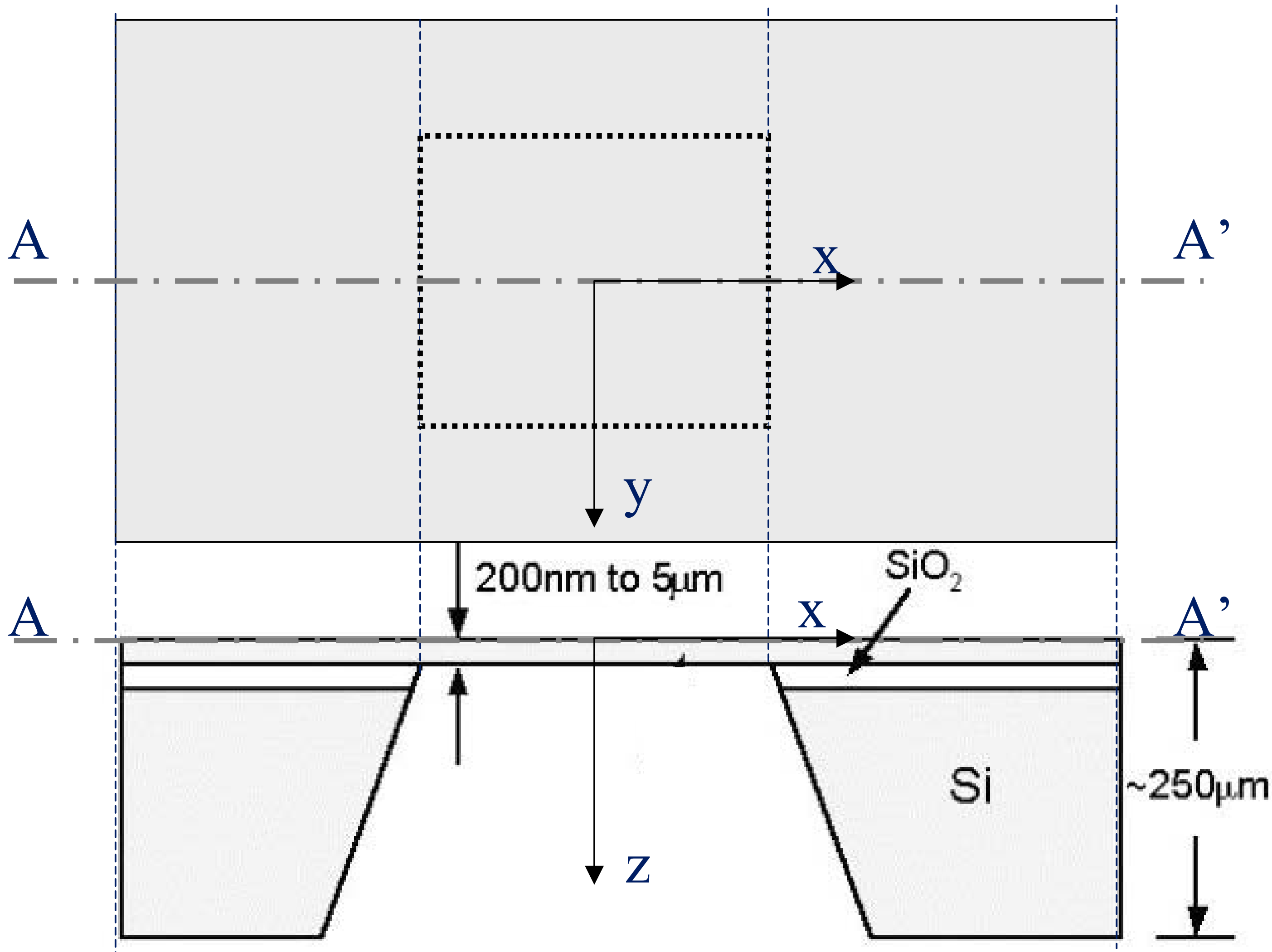
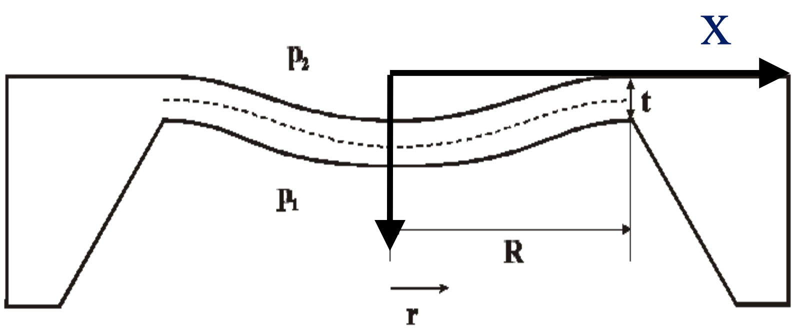
   2.2 sensore MAP (MOTOROLA)

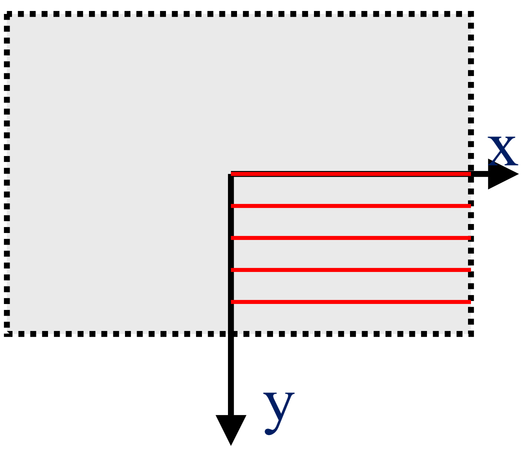
Membrane MEMS in silicio



Deformazione e sforzo sulla membrana

(S.K.Clark &K.D. Wise, IEEE Tr. ED 26, 1979)





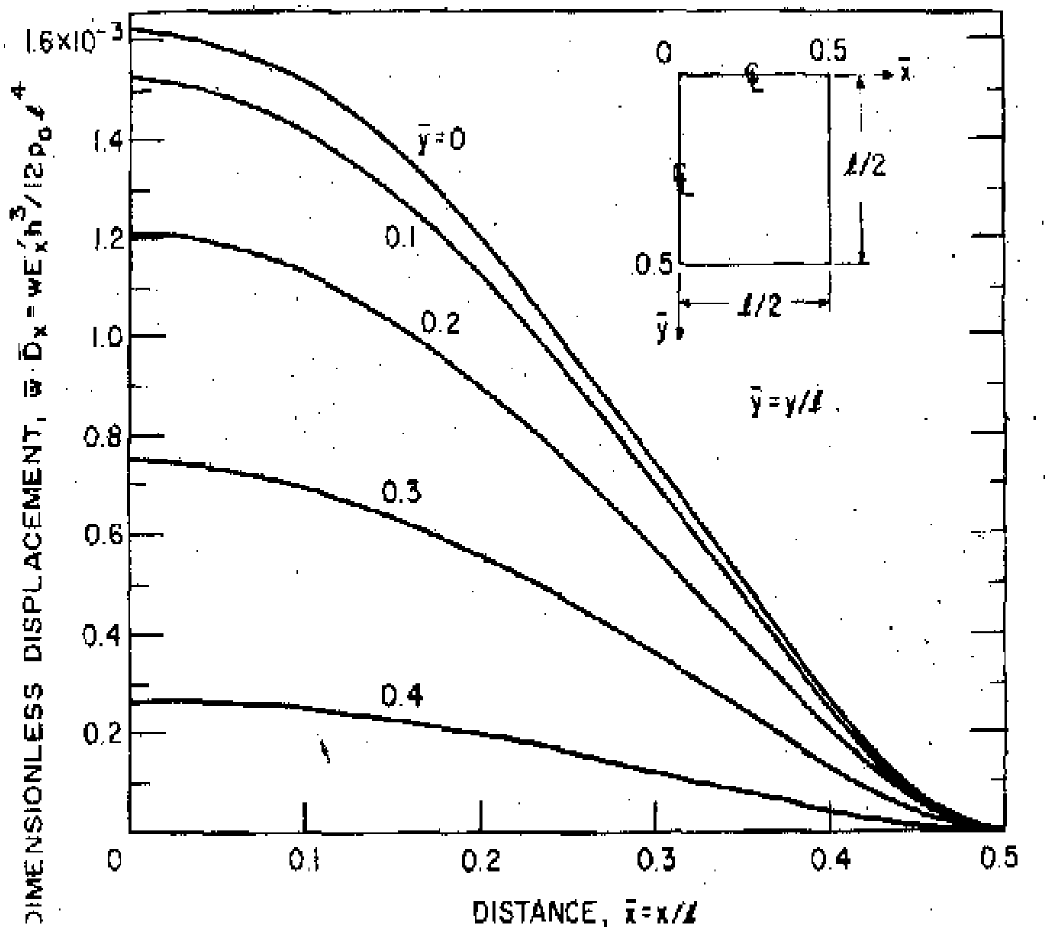
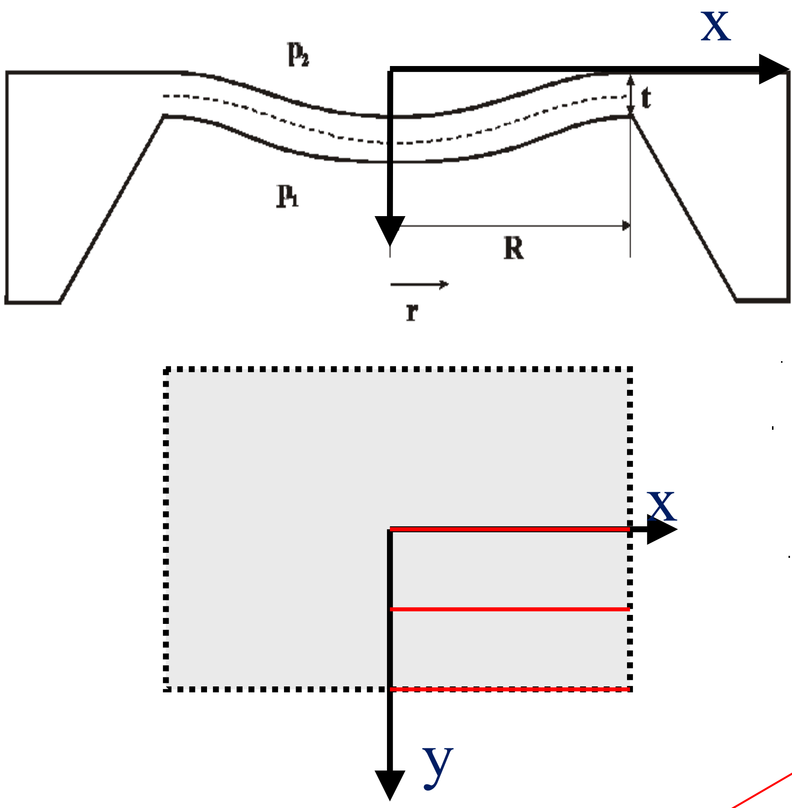


Fig. 4. Dimensionless displacement of a square silicon diaphragm having built-in edges as a function of position on the diaphragm.

Deformazione e sforzo sulla membrana

(S.K.Clark &K.D. Wise, IEEE Tr. ED 26, 1979)



$$\sigma_{xxmax} = 0.3\ p\ (L/H)^2$$

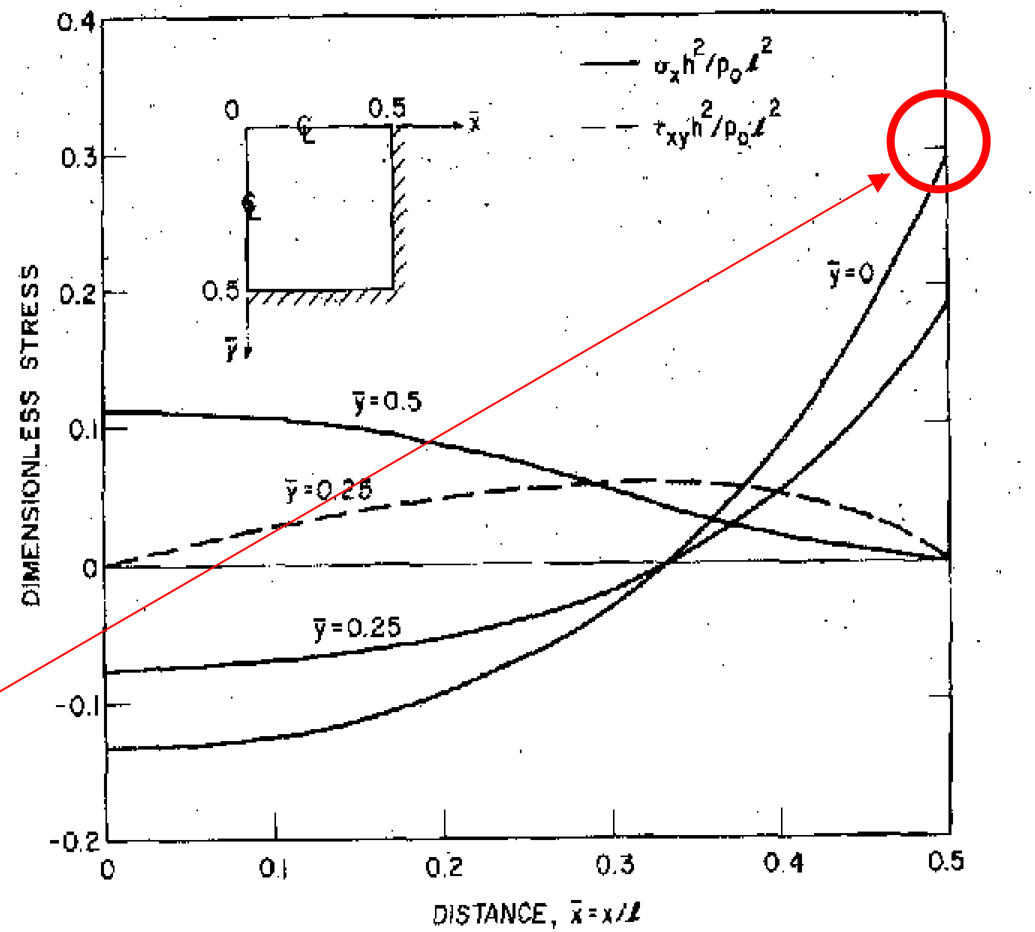
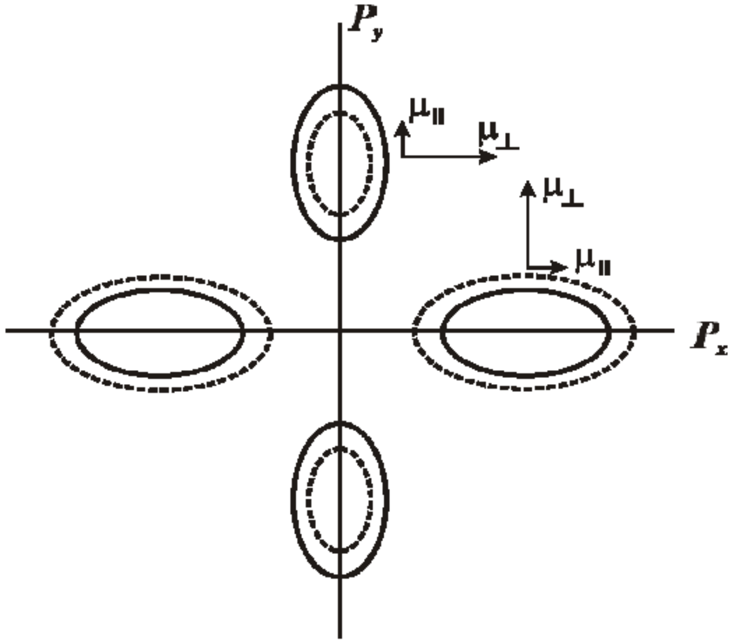


Fig. 5. Dimensionless stress distributions on a silicon diaphragm having built-in edges.

Sensori piezoresistivi



$\Delta\rho/\rho_0 = \pi\ \sigma$

ρ- resistività del silicio

σ- sforzo

$$\mathbf{E} = \rho_e\,[1 + \mathbf{\Pi}\,\sigma]\,\mathbf{J}$$

Electric field

Resistivity tensor

Stress

Current density

Sensori piezoresistivi

$$\mathbf{E} = \rho_e \, [1 + \mathbf{\Pi} \, \sigma] \, \mathbf{J}$$

$$\begin{pmatrix} (\Delta\rho/\rho)_{11} \\ (\Delta\rho/\rho)_{22} \\ (\Delta\rho/\rho)_{33} \\ (\Delta\rho/\rho)_{23} \\ (\Delta\rho/\rho)_{13} \\ (\Delta\rho/\rho)_{12} \end{pmatrix} = \begin{pmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{pmatrix}$$

Sensori piezoresistivi

$$\mathbf{E} = \rho_e \, [1 + \mathbf{\Pi} \, \sigma] \, \mathbf{J}$$

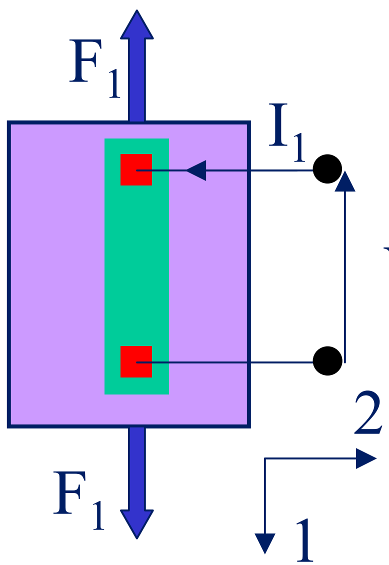
$$\frac{E_1}{\rho_e} = [1 + \pi_{11}\sigma_{11} + \pi_{12}(\sigma_{22} + \sigma_{33})] \, J_1 + \pi_{44}(\sigma_{12}J_2 + \sigma_{13}J_3)$$

$$\frac{E_2}{\rho_e} = [1 + \pi_{11}\sigma_{22} + \pi_{12}(\sigma_{11} + \sigma_{33})] \, J_2 + \pi_{44}(\sigma_{12}J_1 + \sigma_{23}J_3)$$

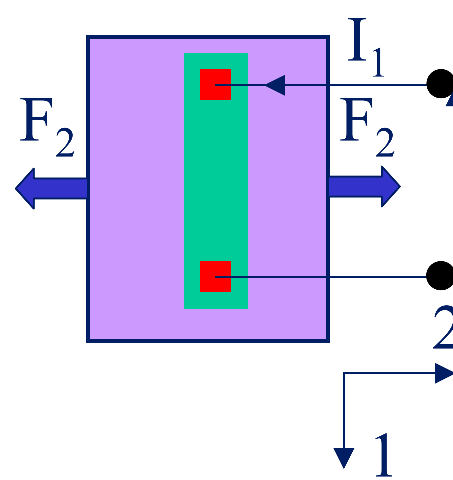
$$\frac{E_3}{\rho_e} = [1 + \pi_{11}\sigma_{33} + \pi_{12}(\sigma_{11} + \sigma_{22})] \, J_3 + \pi_{44}(\sigma_{13}J_1 + \sigma_{23}J_2)$$

$$\frac{E_1}{\rho_e} = [1+ \pi_{11}\sigma_{11} + \pi_{12}(\sigma_{22} + \sigma_{33})]\, J_1 + \pi_{44}(\sigma_{12}J_2 + \sigma_{13}J_3)$$

Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ω -cm	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1



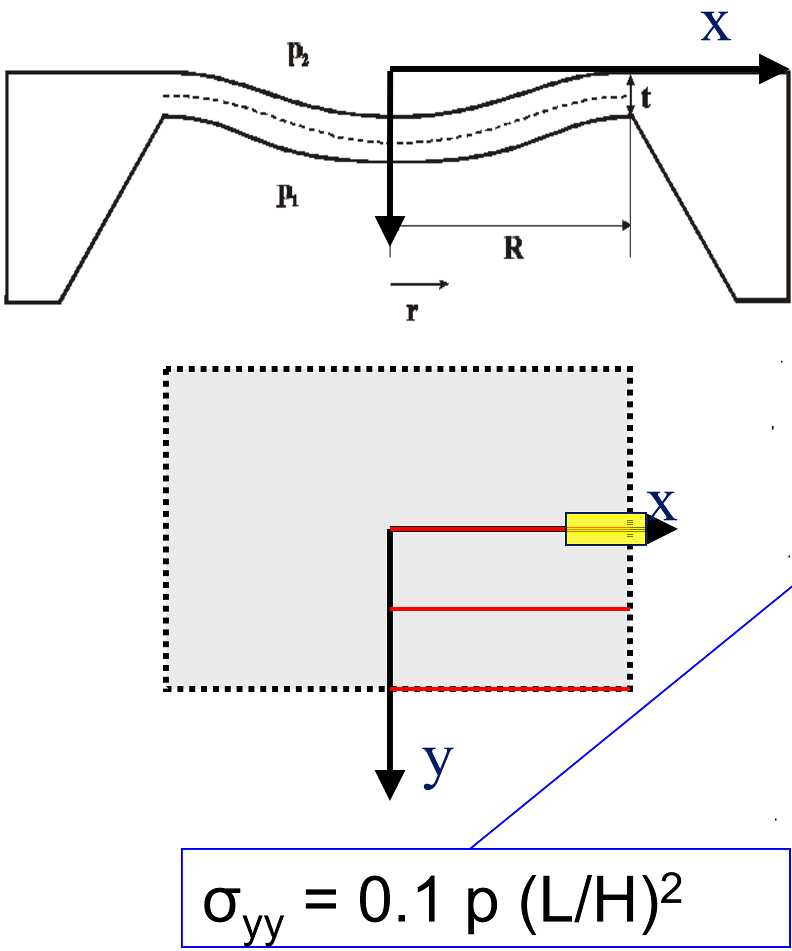
$\pi_l = \pi_{11}$



$\pi_t = \pi_{12}$

Sforzo longitudinale e sforzo trasversale

(S.K.Clark &K.D. Wise, IEEE Tr. ED 26, 1979)



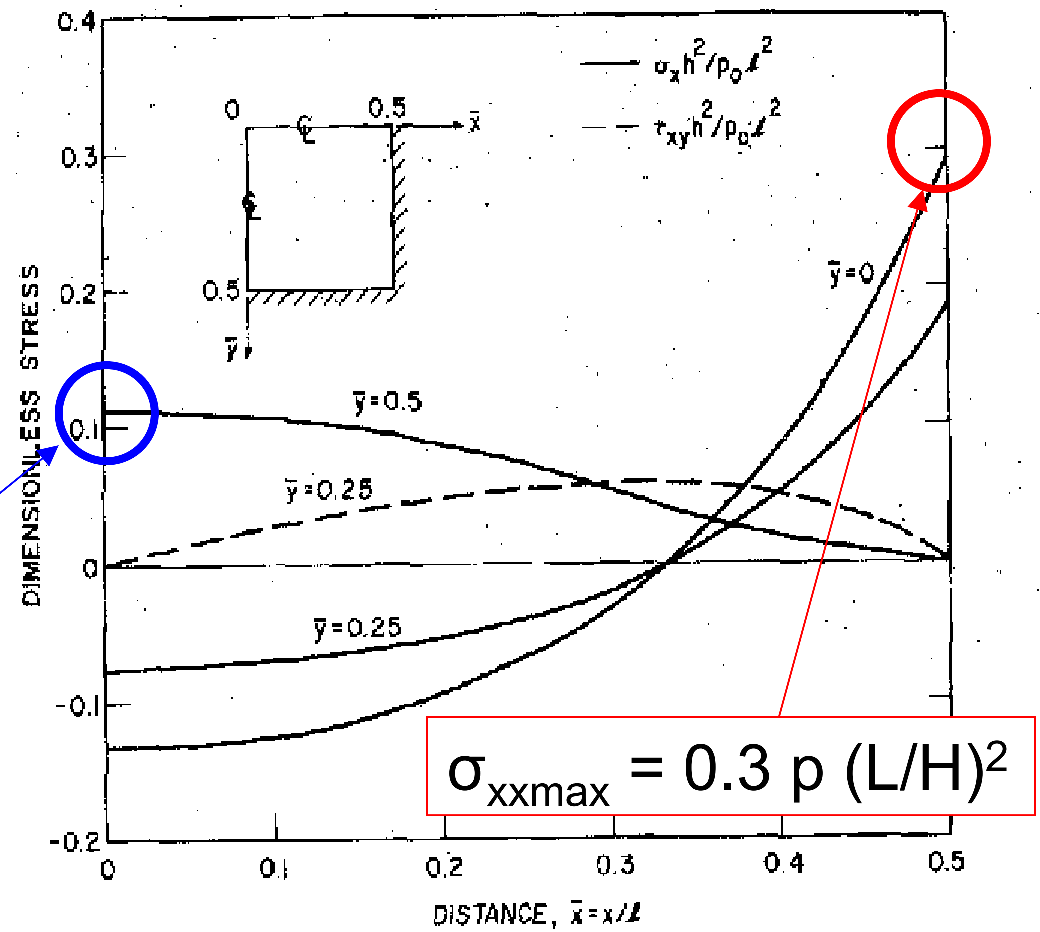


Fig. 5. Dimensionless stress distributions on a silicon diaphragm having built-in edges.

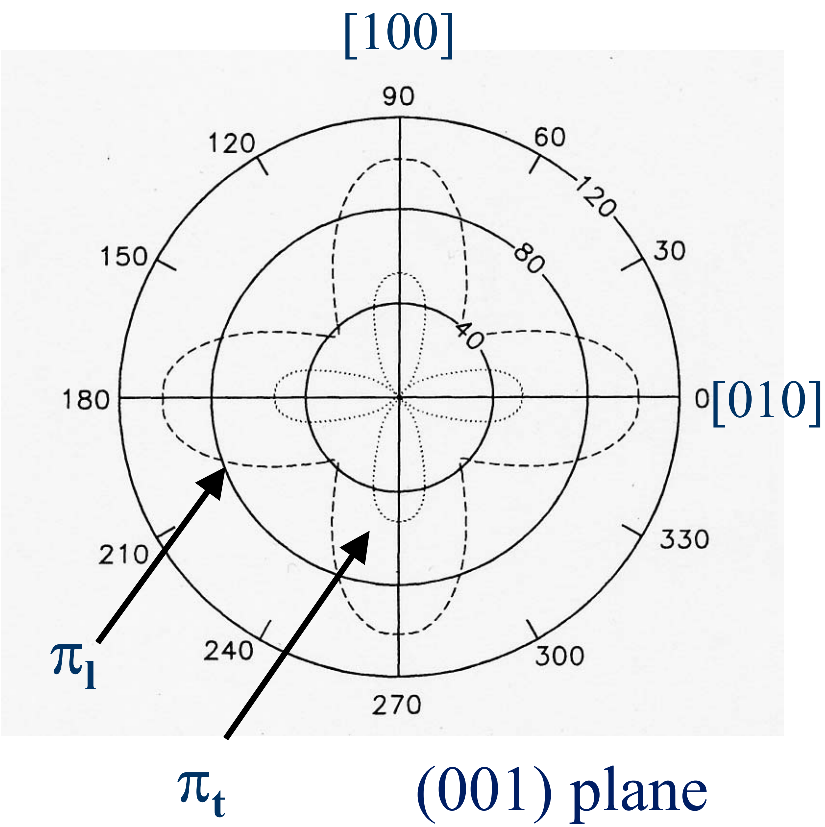
$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \quad \text{l: longitudinal, t: transverse}$$

Longitudinal direction	π_l	**Transverse direction**	π_t
[100]	π_{11}	[010]	π_{12}
[110]	$1/2\ (\pi_{11}+\pi_{12}+\pi_{44})$	$[\bar{1}10]$	$1/2\ (\pi_{11}+\pi_{12}-\pi_{44})$

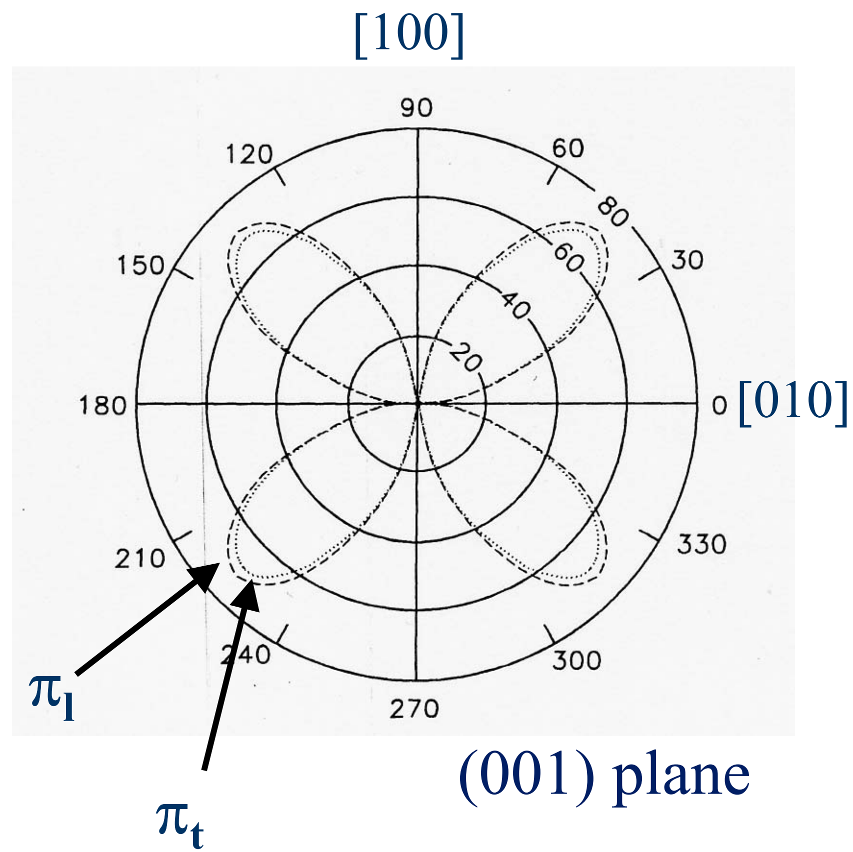
↓

Rappresentazione grafica
dei coefficienti piezoresistivi longitudinale e trasversale
(Y. Kanda, IEEE Tr. ED 29, 1982)

Longitudinal & Transverse piezoresistance coefficients

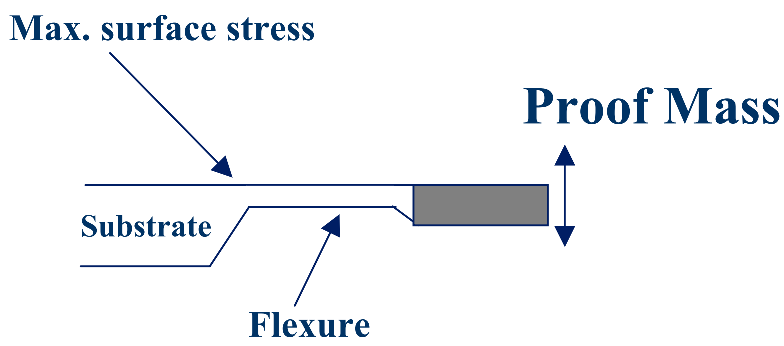


n-type Si



p-type Si

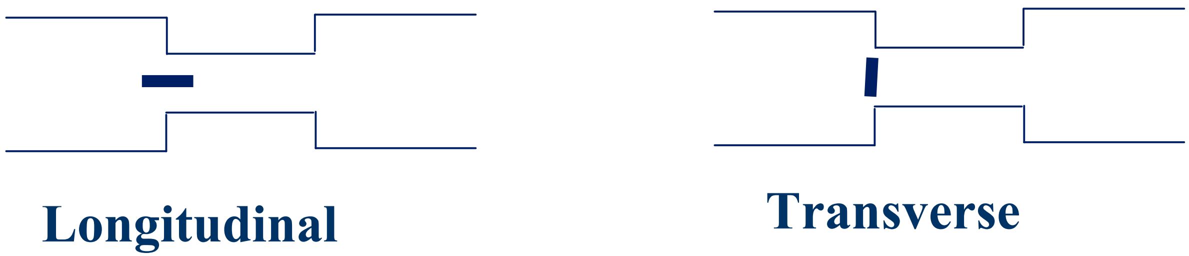
Concept of a piezoresistive sensing scheme



If piezo-resistor is along [110]:

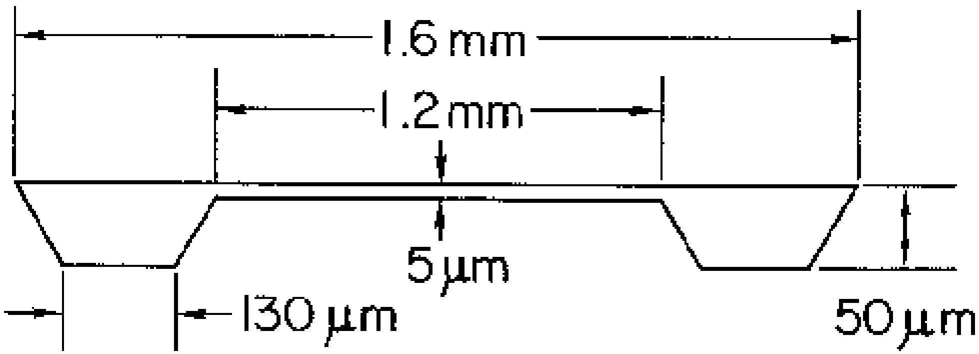
n-type: π_l: $-31.2 \cdot 10^{-11}$ Pa^{-1}, π_t: $-17.6 \cdot 10^{-11}$ Pa^{-1}

p-type: π_l: $71.8 \cdot 10^{-11}$ Pa^{-1}, π_t: $-66.3 \cdot 10^{-11}$ Pa^{-1}



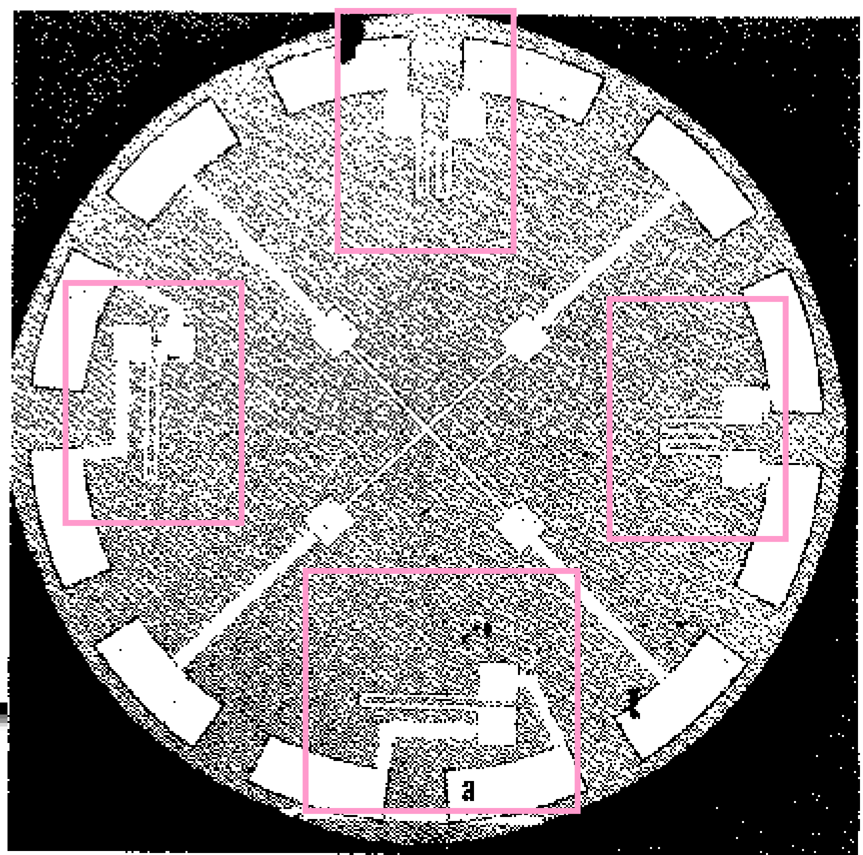
Sensore di pressione piezoresistivo

(S. Samaun et al., “An IC Piezoresistive Pressure Sensor for Biomedical Instrumentation”, ISSCC 1971)

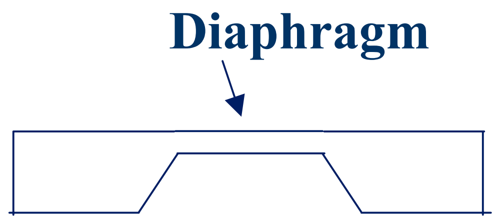


realizzazione delle resistenze:

layout delle resistenze →

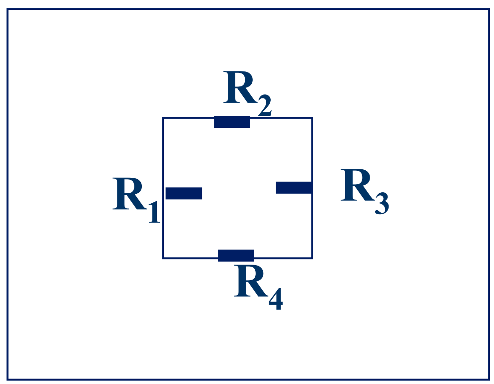


CROSS-SECTION



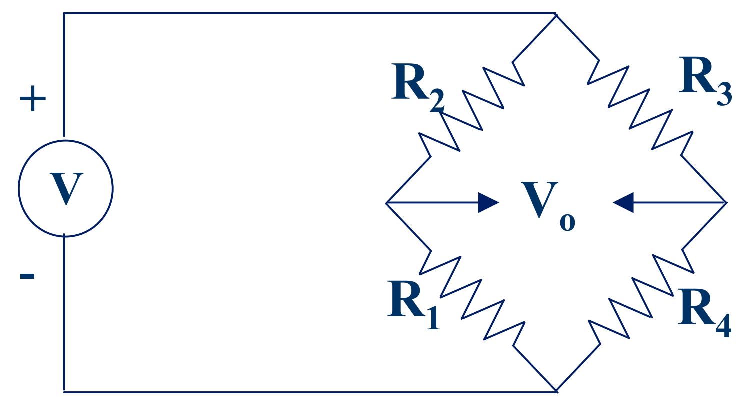
$$\frac{\Delta R_1}{R_1} = \pi_l \sigma_l + \pi_t \sigma_t$$

TOP VIEW



$$\frac{\Delta R_2}{R_2} = \pi_t \sigma_l + \pi_l \sigma_t$$

WHEATSTONE BRIDGE

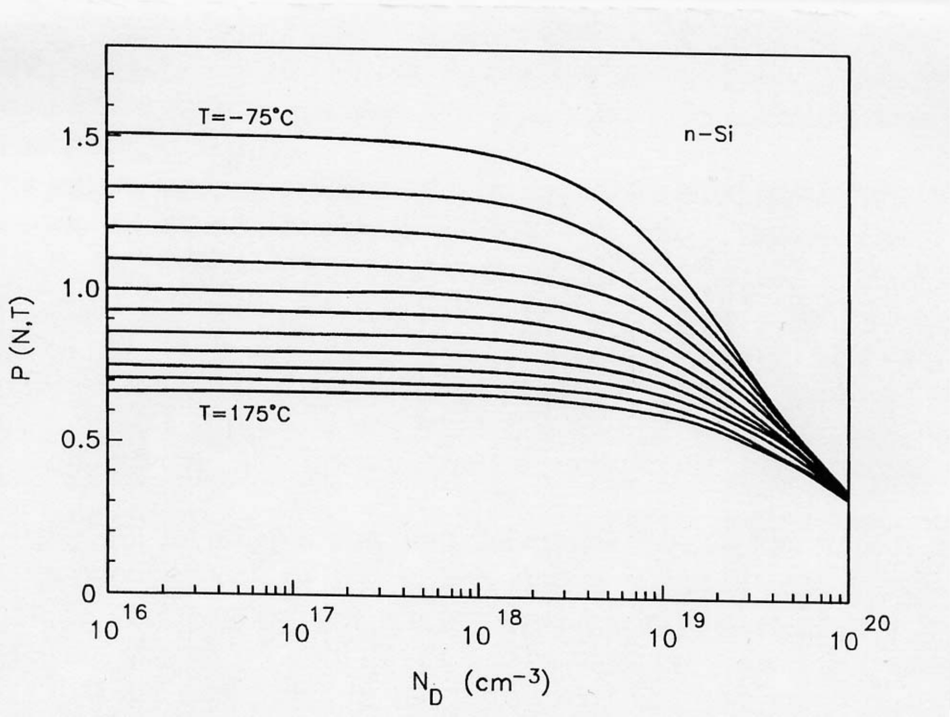


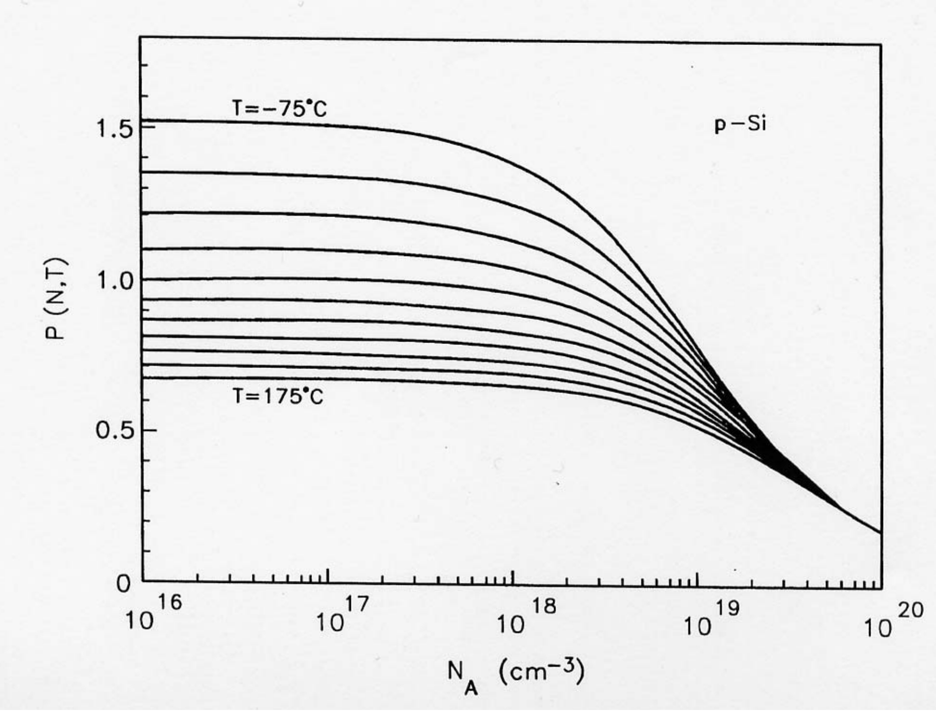
$$R_1 = R_3 = (1 + \alpha_1)\, R_o$$
$$R_2 = R_4 = (1 - \alpha_2)\, R_o$$

→ effetti legati alla temperatura

Piezoresistance coefficients as a function of impurity concentration and temperature for n-Si and p-Si

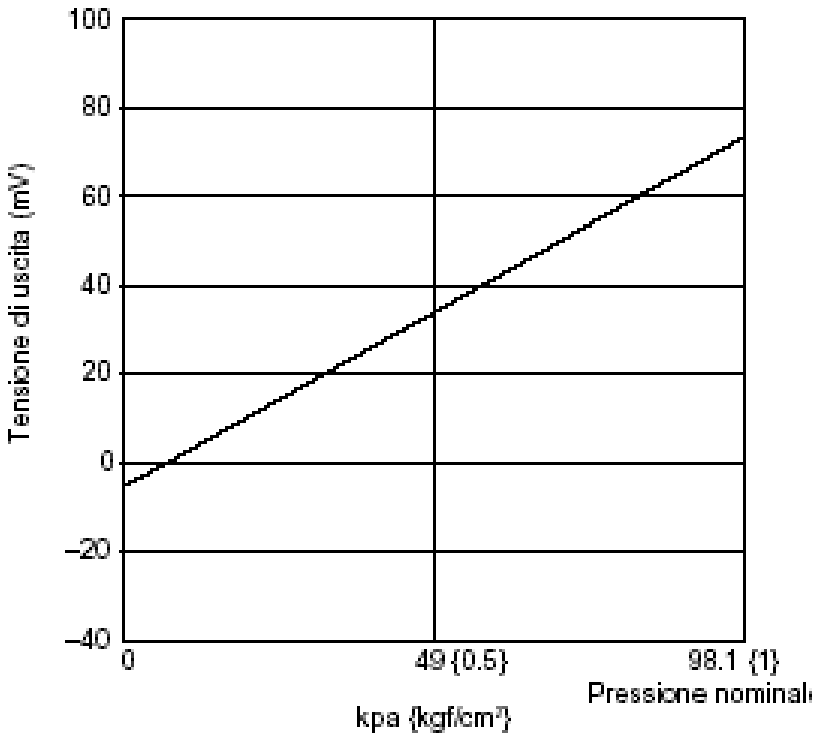
(Y. Kanda, IEEE Tr. ED 29, 1982)



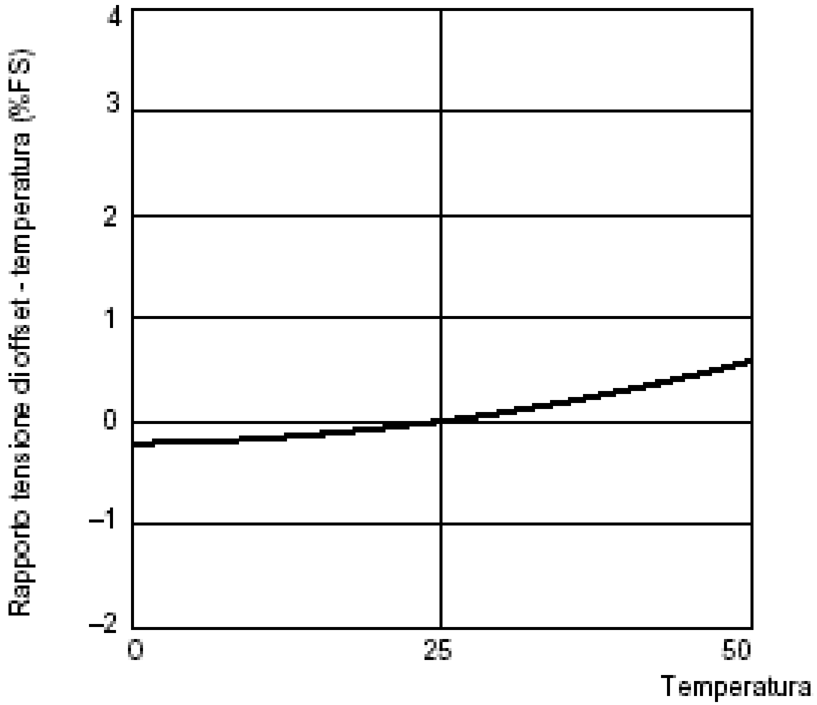


1. Caratteristiche del sensore

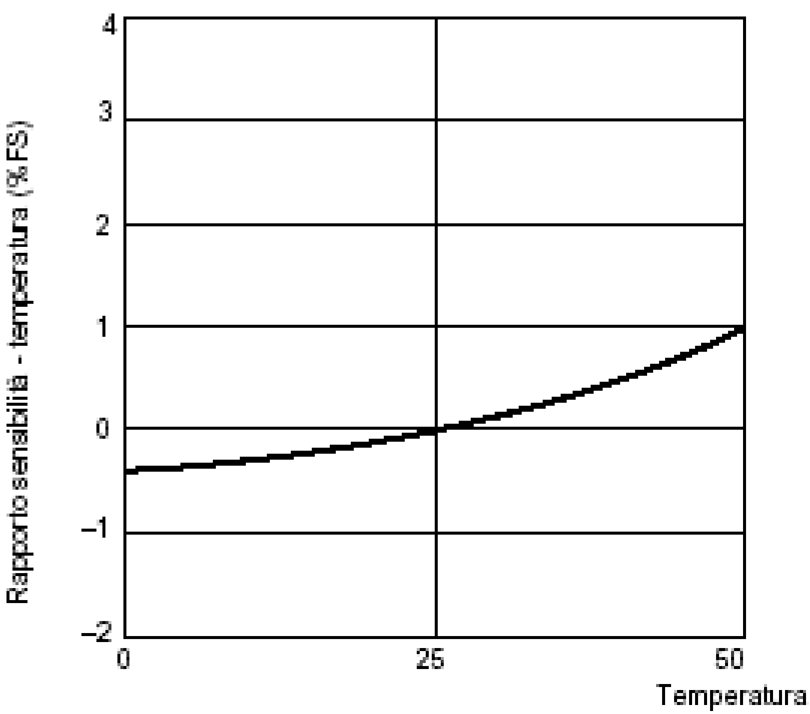
1-<1> Caratteristiche dell'uscita ADP1141
Corrente di esercizio: 1.5 mA;
temperatura: 25°C



1-<2> Rapporto tensione di offset temperatura ADP1141
Corrente di esercizio: 1.5 mA;
valore nominale ±5%FS

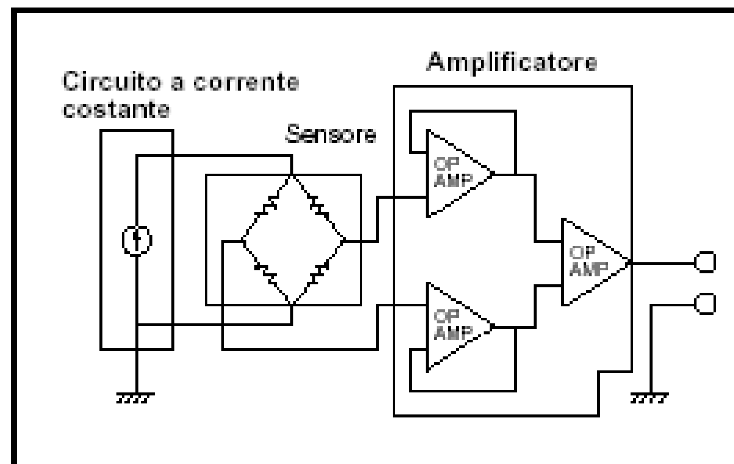


1-<3> Rapporto sensibilità / temperatura (%FS) ADP1141
Corrente di esercizio: 1.5 mA;
Valore nominale ±2.5%FS

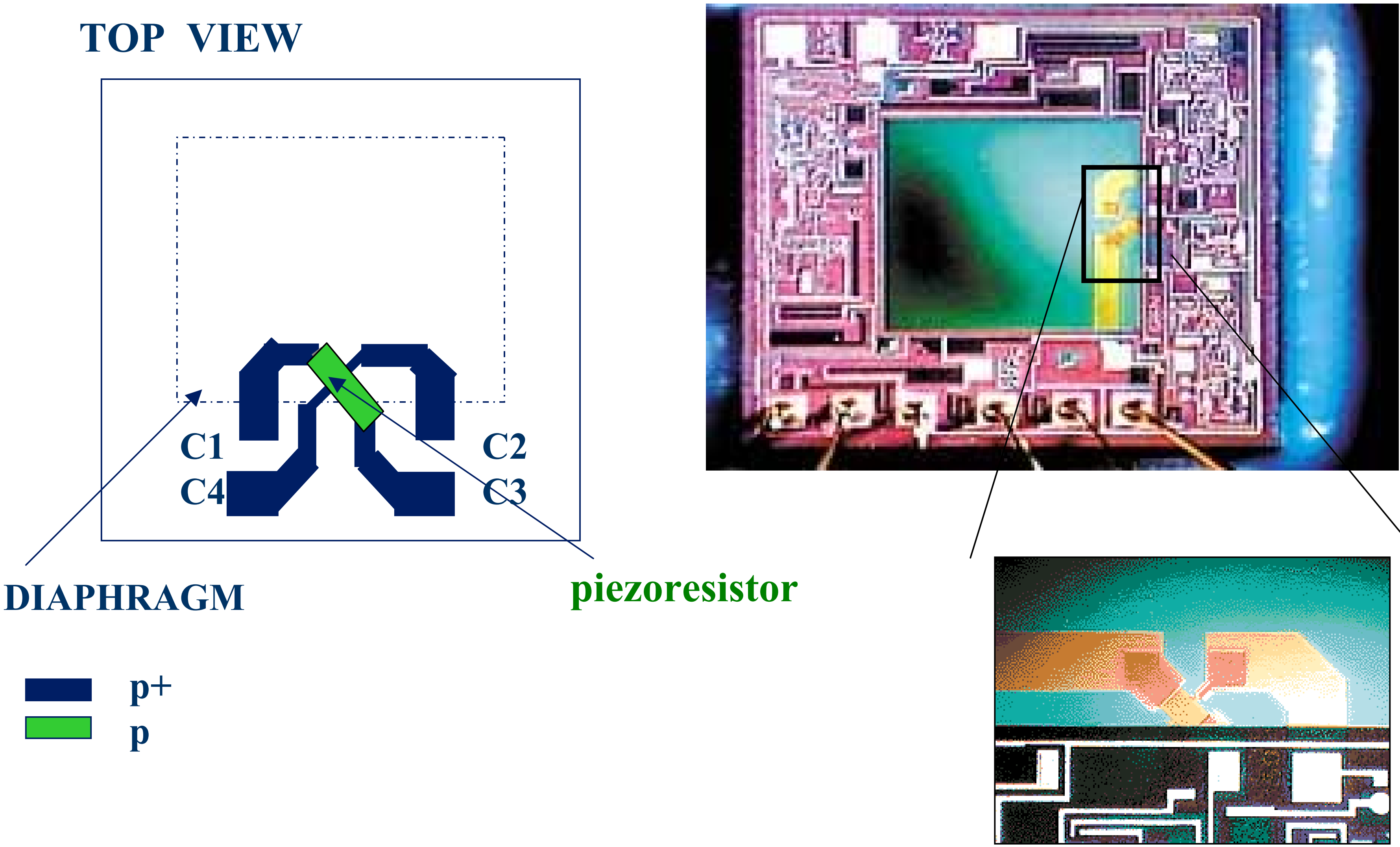


ESEMPIO DI COLLEGAMENTO

La funzione di un sensore di pressione è di trasformare la pressione in un segnale elettrico. La figura rappresenta un tipico esempio di circuito di applicazione dei sensori di pressione.

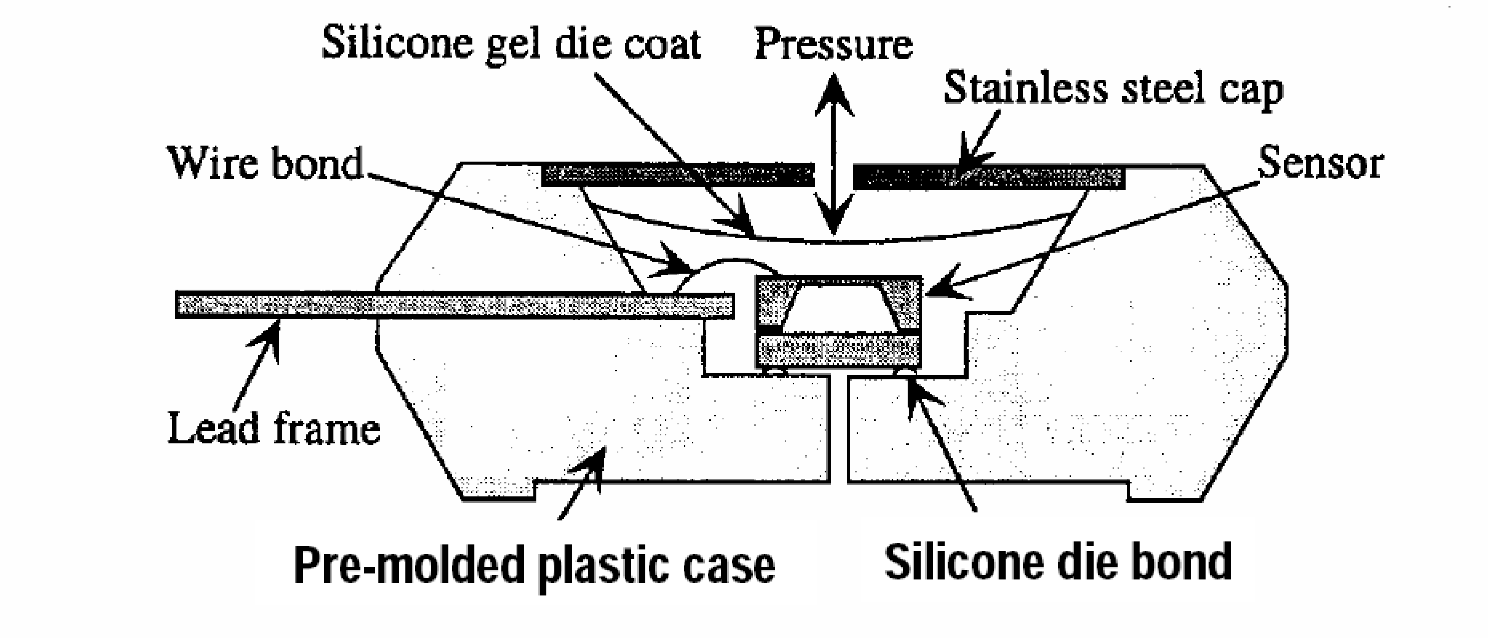


The Motorola X-ducer™ piezoresistor

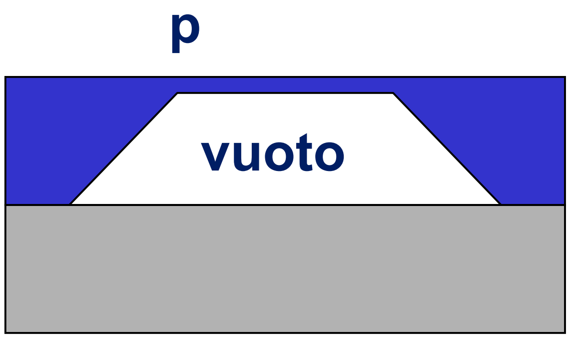


Manifold-Absolute-Pressure (MAP) Sensor by MOTOROLA

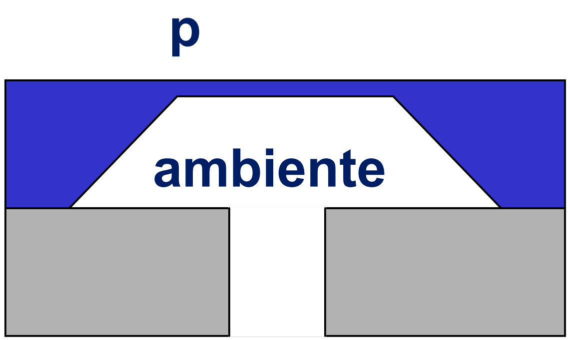
misura la pressione assoluta del flusso di aria nel collettore per calcolare la portata di aria ed il rapporto aria-benzina nel motore. La centralina elettronica calcola il tempo di iniezione adeguandolo dinamicamente.



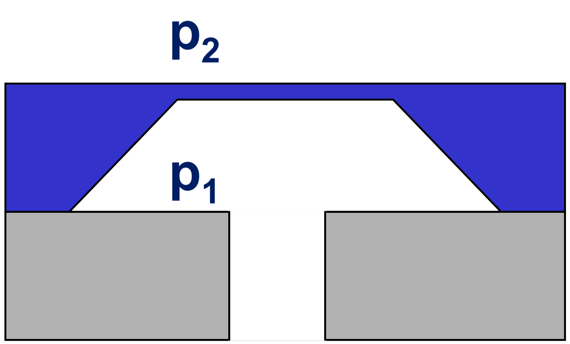
S. Senturia, page 461, Microsystem design



Sensore di pressione assoluta



Sensore di pressione relativa all’ambiente



Sensore di pressione differenziale (p_2-p_1)