Sensors, Signals and Noise

COURSE OUTLINE

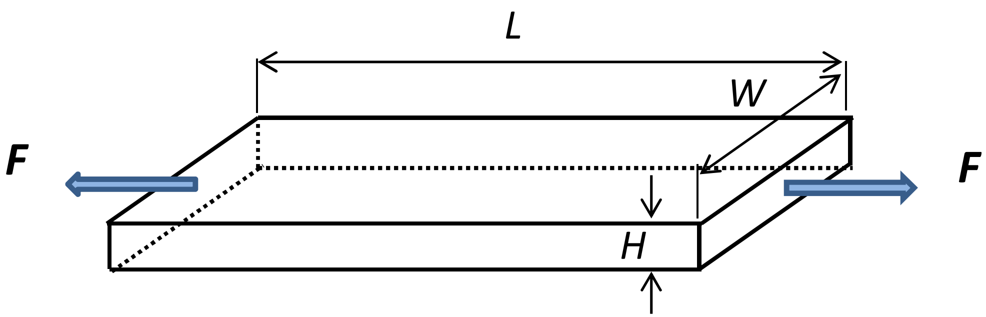
- Introduction
- Signals and Noise
- Filtering
- Sensors: Strain Gauges - SE2

Strain Gauges

- Stress and strain in elastic materials
- Piezoresistive Effect
- Strain Gauge principle
- Strain Gauge Design and Technology
- Electronics for Measurements and Temperature Compensation
- Measure of bending and composite strain
- Semiconductor Strain Gauges

Stress and strain in elastic materials

Stress and Strain in Elastic Material



Metal bar with L = length; W = width; H = thickness; A= W·H cross section
F = pull force applied to the ends

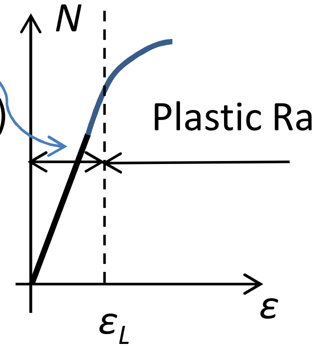
- Stress N = F/A force per unit area
- ΔL = extension of L due to F
- Strain ε = ΔL/L relative variation of L, measured in unit **ΔL/L=10^{-6} = 1μstrain**

Up to the elastic limit ε_L (characteristic of material), strain ε is proportional to stress N.
For currently employed metals (steel, brass, etc.) the limit is $\varepsilon_L < 2\%$

Elastic Range
(reversible deformation)

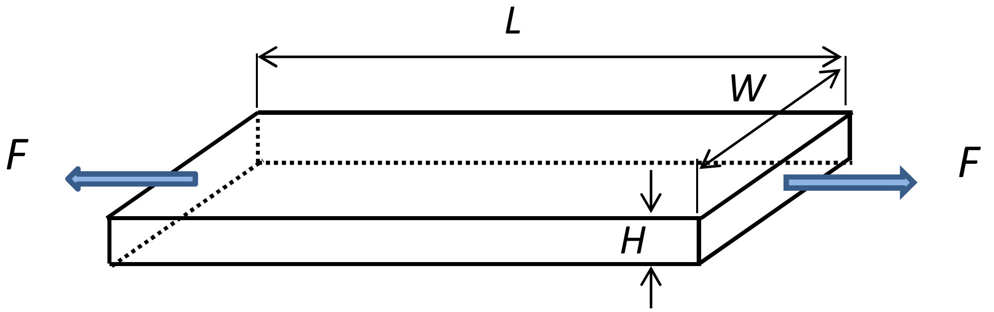
$$\boxed{N = E\varepsilon}$$

***E* Young Modulus** (N/m^2)



Plastic Range (permanent deformation)

Stress and Strain in Elastic Material



In **elastic range,** a pull force F causes:

1) Extension of L proportional to stress: $\varepsilon = N/E$
e.g. for steel E≈ $200 \cdot 10^{12}$ N/m^2 = 200 GPa (1Pa = 1 Pascal=1N/m^2)

2) **Contraction** of the section **dimensions** W and H proportional to the L extension ε

$$-\left(\Delta W/W\right) = -\left(\Delta H/H\right) = \nu \cdot \varepsilon$$

ν **Poisson Ratio** (adimensional number)

For most materials *ν* ≈ from 0,25 to 0,4; for current metals *ν* ≈ from 0,3 to 0,35

3) **Contraction** of the section **area** A= W·H

$$\frac{\Delta A}{A} \approx \frac{\Delta W}{W} + \frac{\Delta H}{H} = 2\nu \cdot \varepsilon$$

Piezoresistive Effect

Piezoresistive Effect

$$\boxed{R = \rho \frac{L}{A} = \frac{L}{\sigma A}}$$

R resistance; ρ resistivity; $\sigma = 1/\rho$ conductivity

- Piezoelectric effect: in various materials a crystal lattice deformation changes the material resistivity, which contributes to the change of macroscopic resistance.
- Strain changes the shape of the energy band curves (energy vs momentum E-k), hence changes the electron effective mass m* and therefore the carrier mobility
- Semiconductors have strong piezoresistive effect and the dependence of conductivity on the strain is markedly nonlinear and strongly dependent on the semiconductor doping and on the temperature
- Metals have small or moderate effect, somewhat higher for Nickel and alloys than other metals. The dependence of conductivity on the strain N is fairly linear and a **piezoresistivity coefficient β** can be defined

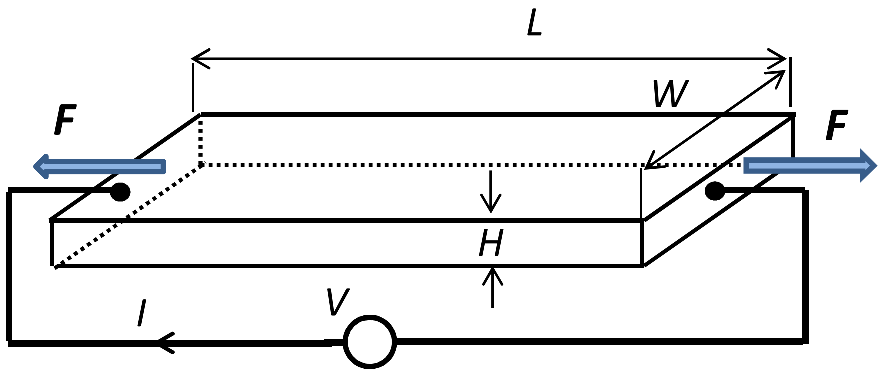
$$\rho = \rho_o \left(1 + \beta N\right)$$

and the relative variation due to the piezoresistive effect can be described as

$$\frac{\Delta\rho}{\rho_o} = \beta N = \beta E \cdot \varepsilon$$

Strain Gauge principle

Strain Gauge Principle



$$R = \rho \frac{L}{A} = \frac{L}{\sigma A}$$

R resistance; ρ resistivity; $\sigma = 1/\rho$ conductivity

- In principle, a **Strain Gauge** (SG) is a long and thin metal slab (small cross section H << L and W << L) employed to measure the strain ε along its length L
- It is employed to measure strain in elastic range, without permanent deformation
- The relative variation of R is small (small elastic deformation and small or moderate piezoresistive effect) and can be **evaluated in first-order approximation***, i.e. denoting by subscript «o» the quiescent values without strain

$$\frac{\Delta R}{R_o} = \frac{\Delta L}{L_o} - \frac{\Delta A}{A_o} + \frac{\Delta \rho}{\rho_o} = \varepsilon + 2\nu\varepsilon + \beta E\varepsilon = \varepsilon\left(1 + 2\nu + \beta E\right)$$

* The finite small variation is computed as a differential

Gauge Factor

$$\frac{\Delta R}{R_o} = \frac{\Delta L}{L_o} - \frac{\Delta A}{A_o} + \frac{\Delta \rho}{\rho_o} = \varepsilon + 2\nu\varepsilon + \beta E\varepsilon = \varepsilon\left(1 + 2\nu + \beta E\right)$$

- The conversion gain from strain ε to relative variation of the SG resistance R is called **Gauge Factor *G***

$$\boxed{G = \frac{\left(\Delta R / R_o\right)}{\varepsilon} = 1 + 2\nu + \beta E}$$

- Metal SG have small or moderate G:

  G from 1,8 to 2,2 for most metals

  G from 2 to 3,5 for Ni-Cu and Ni-Fe-Cr alloys

  G≈12 for Nickel

  Since metals have about $\nu \approx 0,3$ a metal SG without piezoresistivity (i.e. with β=0) would have

  G≈ 1,6

  A comparison with the actual *G* values shows that the piezoresistivity contribution is significant, but it is not a big one

Strain Gauge Design and Technology

Design of Strain Gauge Devices

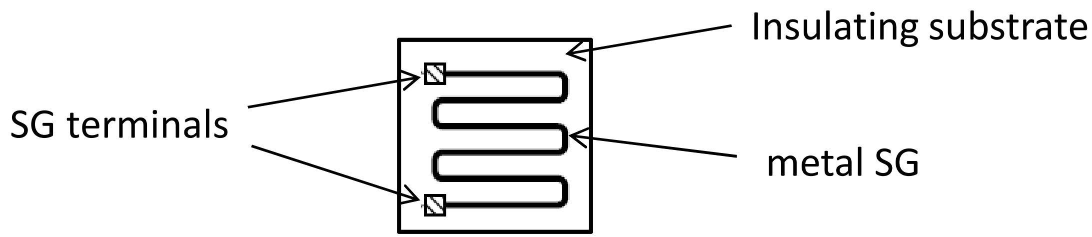
Conflicting requirements condition the design and fabrication of SG devices

a) Requirement: SG fastened to the sample under test for having the same strain
Solution: SG fastened onto a robust thin foil, which is then glued to the sample

b) Requirement: SG electrically isolated from the sample under test, for avoiding shunt effects due to conductive samples
Solution: SG supporting foil in insulating material

c) Requirement: small size of SG, for measuring the local strain and not strain averaged over a fairly wide area
Solution: limited size of the SG foil, as required by the case under test

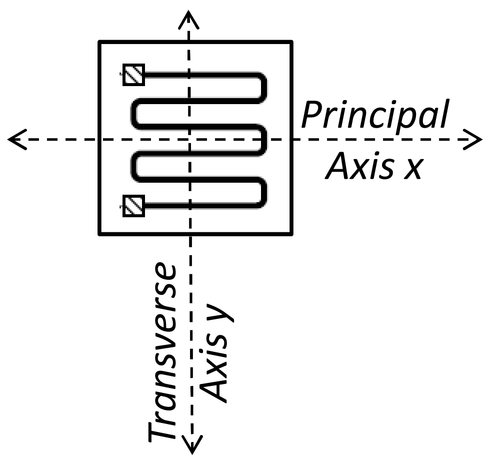
d) Requirement: not too small resistance of SG, for limiting measurement errors and uncontrolled parasitic effects (electrical contact resistance, etc.):
Solution: meander configuration of the resistor, in order to fit a long conductor length into the small area of the foil



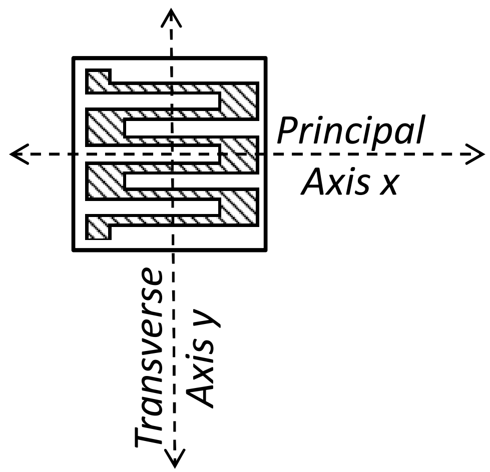
Design of Strain Gauge Devices

- Old fashioned **wound-wire technology**: long thin **metal wire** wound in meander and fastened on insulating foil; strain measured on Principal Axis x (direction of meander long portions) with Principal Gauge Factor G_P
- Main drawbacks: a) sensitive also to strain along Transverse Axis y, though with a minor Transverse Gauge Factor $G_T \approx 0{,}05\ G_P$ b) moderate precision and reproducibility; well-matched SG samples are not available
- Modern **lithographic technology**: exploits lithographic technology (well developed in different scales for printed circuit boards and for integrated circuits) for finely designing SG of small size (1 cm and less) in a **very thin metal layer (from 2 to 10 µm) coated over an insulating foil**

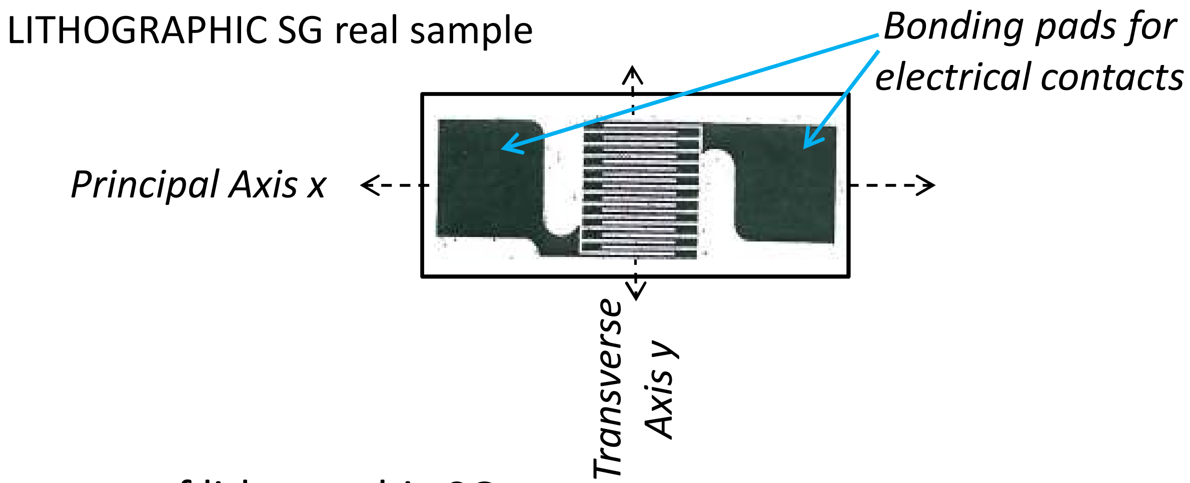
WOUND-WIRE SG outline



LITHOGRAPHIC SG outline



Design of Strain Gauge Devices



Advantages of lithographic SG

- Wide transversal portions of the meander: their contribution to the SG resistance R is small so that the Transverse Gauge Factor is negligible $G_T < 0{,}001\ G_P$
- Small size < 1cm
- Metal conductor thickness in micron range gives high resistance per unit path; current R values are from 50Ω to 2kΩ, special SG are available with R>10kΩ
- Precisely defined device features, small tolerances in industrial production
- High reproduciblity: well matched SG devices are currently available
- The wide exposed surface area facilitates dispersion of heat generated in the resistor, thus reducing the SG self-heating

Electronics for Measurements
and
Temperature Compensation

Electronic Measurements with Strain Gauges

As concerns the electronic measurement techniques, **Strain Gauges and Resistance Temperature Detectors (RTD) are essentially the same case**: small variations of a small resistance (typically a few hundred Ohms) must be measured with high precision.

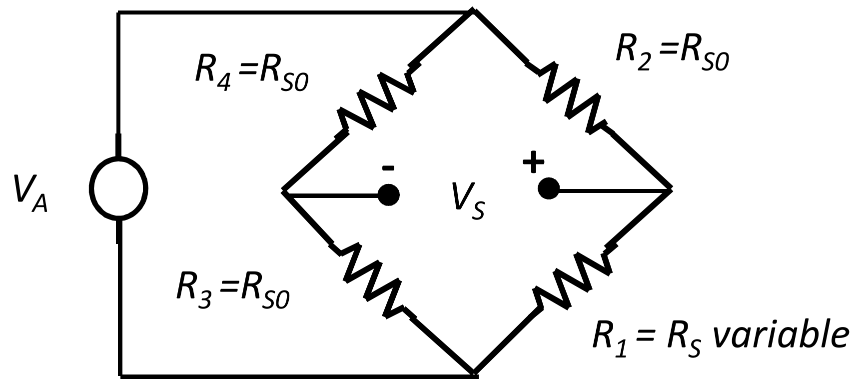
We will thus make explicit reference to the treatment of RTDs and add some notes about specific issues of SGs

- The SG resistance is $R_S = R_{S0} + \Delta R_S = R_{S0} + G\varepsilon R_{S0}$
- The Wheatstone Bridge with equal resistors (SG and other resistors with value R_{S0}) is a rational and widely employed solution. With small variations $\Delta R_S / R_{S0} << 1$ the signal V_S is proportional to the strain ε (as computed at 1st-order)

For a W-bridge with

- one SG of variable R_S
- three constant R_{S0}

$$\boxed{V_S = \frac{V_A}{4}\frac{\Delta R_S}{R_{S0}} = \frac{V_A}{4} G \cdot \varepsilon}$$



Temperature Effect in Strain Gauges

- The resistivity of metals increases with the temperature

  $\rho = \rho_0 + \Delta\rho = \rho_0 + \alpha\, \Delta T\, \rho_0$ (α temperature coefficient of the metal)

  for metals employed in SG it's around $\alpha \approx 4 \cdot 10^{-3}$ /K .

- Comparing R_S variations due to strain ε and to a temperature variation ΔT

$$\left(\frac{\Delta R_S}{R_{S0}}\right)_N = G\varepsilon \qquad\qquad \left(\frac{\Delta R_S}{R_{S0}}\right)_T = \alpha\, \Delta T$$

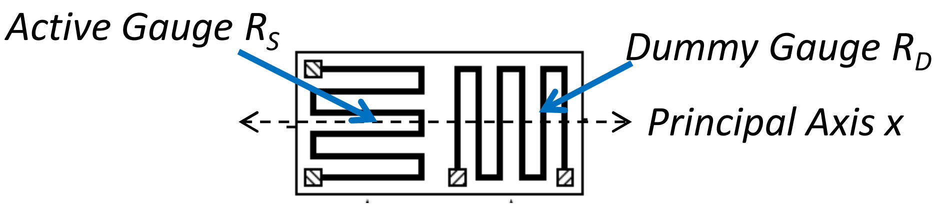
  we see that if the SG temperature T has an even small deviation $\Delta T = T - T_0$ from the reference temperature T_0 of the other resistors in the bridge, a remarkable error ε_T ensues. In fact, with $\alpha \approx 4 \cdot 10^{-3}$ /K and $G \approx 2$ the error is

$$\varepsilon_T = \frac{\alpha\, \Delta T}{G} \approx 2 \cdot 10^{-3} \Delta T = 2000 \cdot \Delta T \left[in\ K\right]\ microstrain$$

- SG temperature deviations are often met in practice (e.g. SG working on motors or other structures with variable temperature) and produce unacceptable errors. Temperature effects in the SG cannot be avoided, but accurate **compensation** of their effect can be obtained by inserting in the Wheatstone bridge a properly devised **dummy gauge**

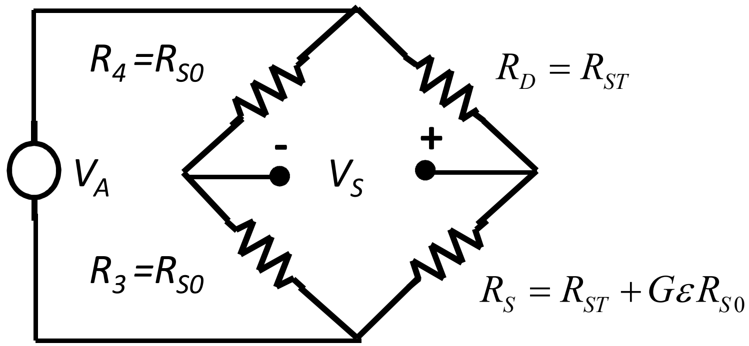
Compensation of Temperature Effects

Compensated dual SG outline



$$\boxed{R_S = R_{S0} + \alpha\,\Delta T\,R_{S0} + G\varepsilon R_{S0} = R_{ST} + G\varepsilon R_{S0}}$$

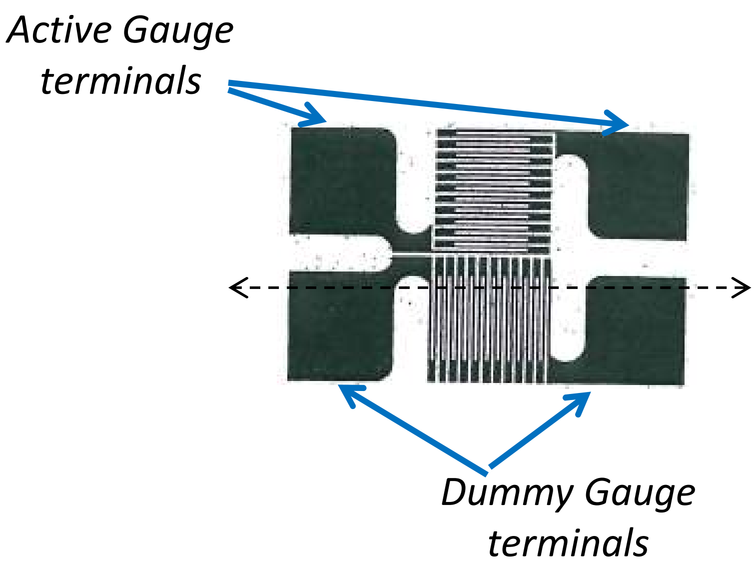
$$\boxed{R_D = R_{S0} + \alpha\,\Delta T\,R_{S0} = R_{ST}}$$

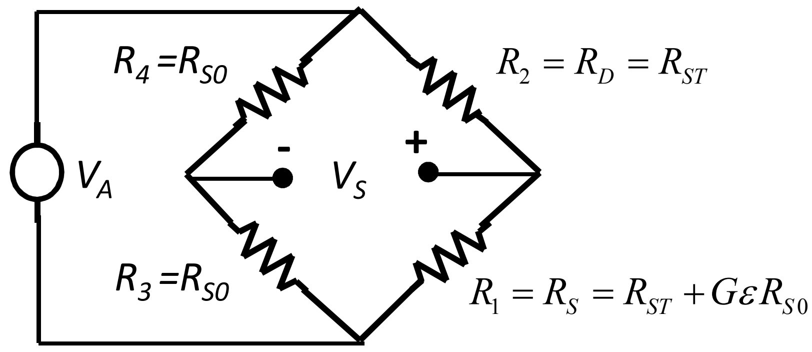


- Two identical gauges (Active Gauge and Dummy Gauge) are placed on the same foil with principal axes orthogonal
- The foil is glued to the structure under test, with principal axis of the active gauge in the direction of the strain to be measured
- The strain of the structure tested modifies the resistance R_S of the active gauge, but not the resistance R_D of the dummy gauge
- Active and dummy gauge in close contact with the structure tested are kept at the same temperature of the structure
- The power dissipation in the resistors must be limited by limiting the supply voltage V_A , in order to limit the SG self-heating

Compensation of Temperature Effects

Compensated dual SG real sample





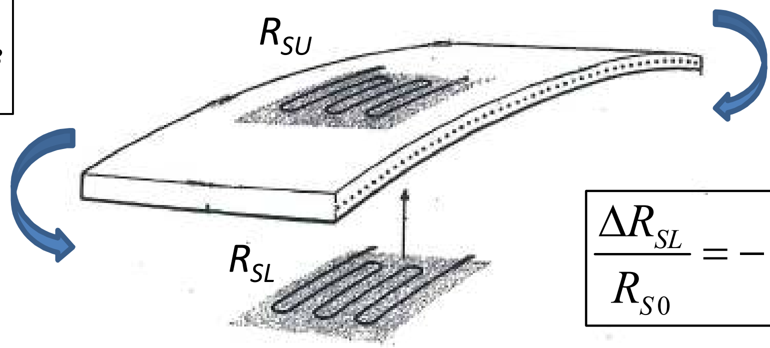
- In the bridge configuration shown (active gauge R_S inserted in R_1 position, dummy gauge R_D in R_2 position) the effects on the output voltage V_S of the temperature variation in R_S and R_D are compensated, hence V_S depends only on the strain ε
- Other alternative configurations of the bridge can be employed for compensation of the temperature effects; e.g. R_S inserted in R_1 position and R_D in R_3 position

Measure of bending and composite strain

Measure of bending and composite strain

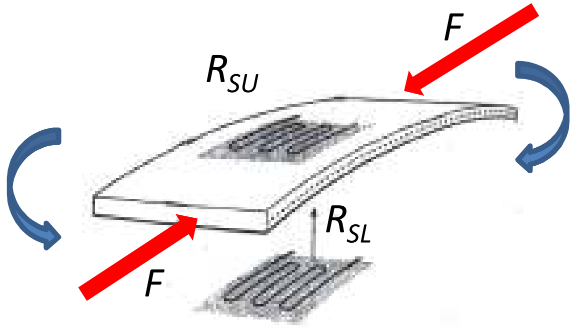
- With one Strain Gauge just a component of the strain is measured, the tensile or compressive strain in the direction of the SG principal axis.
- However, other strain components can be measured with more SGs rationally combined in the Wheatstone bridge
- Let's consider bending a long board with rectangular section (see the figure). The upper surface experiences a tensile strain $\boldsymbol{\varepsilon_B}$, the lower surface a symmetrical compressive strain **-** $\boldsymbol{\varepsilon_B}$. In fact, the strain linearly varies in the board section from $\boldsymbol{\varepsilon_B}$ to $\boldsymbol{-\varepsilon_B}$ and is zero in the mid, which is called «neutral plane»
- Let's consider to apply on the two surfaces of the board two matched SG (with equal resistance R_{S0} and Gauge factor G), denoted as R_{SU} on the upper surface and R_{SL} on the lower surface. Due to bending we get

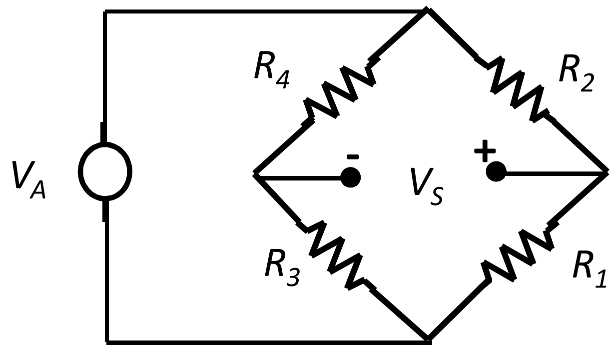
$$\boxed{\frac{\Delta R_{SU}}{R_{S0}} = G\varepsilon_B}$$



$$\boxed{\frac{\Delta R_{SL}}{R_{S0}} = -G\varepsilon_B}$$

Measure of bending and composite strain





- With R_{SU} inserted in the bridge as R_1 and R_{SL} as R_3 , we measure the bending strain $\boldsymbol{\varepsilon_B}$

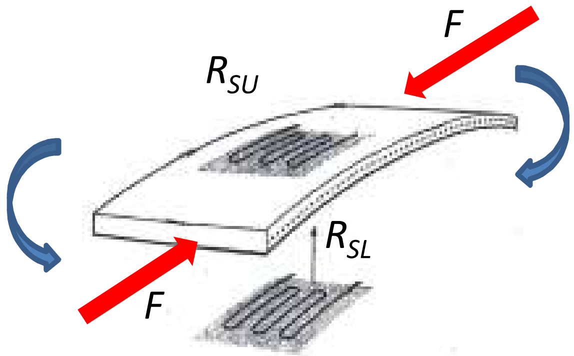
$$V_{SB} = \frac{V_A}{4}\frac{\Delta R_{SU}}{R_{S0}} - \frac{V_A}{4}\frac{\Delta R_{SL}}{R_{S0}} = \frac{V_A}{2} G \cdot \varepsilon_B$$

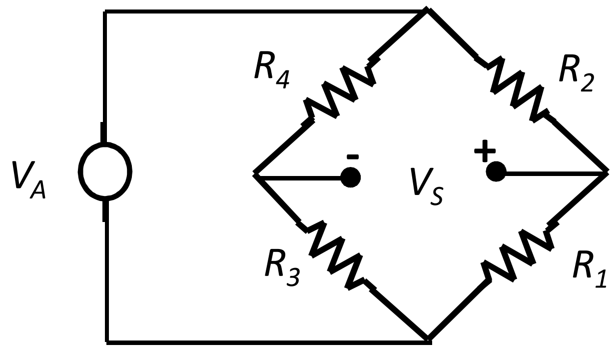
- Let's consider now that a compressive force is added at the board ends: equal strain $\boldsymbol{\varepsilon_F}$ is added at the upper and lower surface, but the two SG have equal variation and the added contribution to the bridge output voltage is zero

$$\frac{\Delta R_{SU}}{R_{S0}} = \frac{\Delta R_{SL}}{R_{S0}} = G\varepsilon_F \Rightarrow V_{SF} = \frac{V_A}{4}\frac{\Delta R_{SU}}{R_{S0}} - \frac{V_A}{4}\frac{\Delta R_{SL}}{R_{S0}} = 0 \Rightarrow \boxed{V_S = V_{SB} + V_{SF} = \frac{V_A}{2} G \cdot \varepsilon_B}$$

- In conclusion, by suitably employing two SG we can separately measure the net bending strain $\boldsymbol{\varepsilon_B}$ also in presence of an axial strain $\boldsymbol{\varepsilon_F}$

Measure of bending and composite strain





- On the other hand, with the same two SG we can also measure separately the net axial strain $\boldsymbol{\varepsilon_F}$ in presence of the bending strain $\boldsymbol{\varepsilon_B}$
- It is sufficient to change the configuration of the bridge. In fact, with R_{SU} inserted as R_1 and R_{SL} as R_4 we get

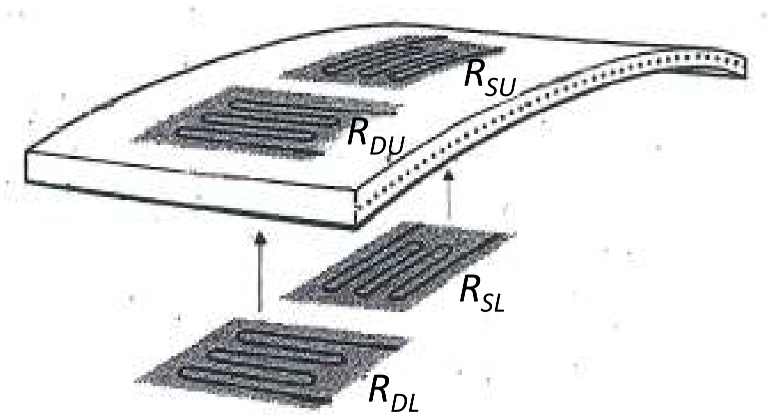
$$V_{SB} = \frac{V_A}{4}\frac{\Delta R_{SU}}{R_{S0}} + \frac{V_A}{4}\frac{\Delta R_{SL}}{R_{S0}} = 0 \qquad V_{SF} = \frac{V_A}{4}\frac{\Delta R_{SU}}{R_{S0}} + \frac{V_A}{4}\frac{\Delta R_{SL}}{R_{S0}} = \frac{V_A}{2} G \cdot \varepsilon_F$$

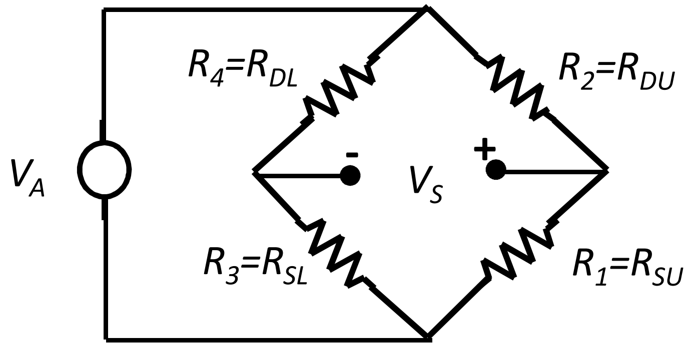
Therefore

$$\boxed{V_S = V_{SB} + V_{SF} = \frac{V_A}{2} G \cdot \varepsilon_F}$$

Measure of bending and composite strain

- The measurements of $\boldsymbol{\varepsilon_B}$ and $\boldsymbol{\varepsilon_F}$ obtained with two matched SG as illustrated are correct only if the two SG are at the same temperature, but in many cases this is not achieved because the two SG are not in close proximity
- The drawback is avoided and the approach extended to all cases simply by
  a) employing dual compensated SGs instead of simple SGs and
  b) inserting in the bridge each dummy gauge in suitable position to compensate the associated active gauge





- Combinations of various SGs can be employed also for measurements in complex strain situations, i.e. with strain components in various directions, e.g. two-dimensional strain in aeronautical structures, such as aeroplane wings

Semiconductor Strain Gauges

Semiconductor Strain Gauges

- Semiconductors such as Germanium and Silicon have very strong piezoresistive effect. Strain Gauges in such materials thus provide large Gauge Factor G in the range from 100 to 300
- Magnitude and sign of the piezoresistive effect are governed by the type and level of doping. In p-type Silicon the effect is positive (tensile strain increases the resistivity) and in n-type silicon it is negative (tensile strain decreases the resistivity)
- The effect is markedly dependent on the temperature, with G decreasing significanly as the temperature is increased. A typical example is a reduction from G=120 at 10°C to G=105 at 65°C.
- The Gauge Factor G is not constant as the strain is increased, i.e. the gauge is not linear, with G decreasing significantly at moderately high strain. A typical example is a decrease from G=125 at 2000 microstrain down to G=100 at 4000 microstrain
- The elastic range of these semiconductor materials is quite narrower than that of metals, the elastic limit is typically at ≈4000 microstrain

Semiconductor Strain Gauges

In summary, semiconductor SGs suffer noteworthy limitations

- Response is not linear
- Response is strongly dependent on the temperature
- Dynamic range is small

but also offer remarkable features, such as

- High Gauge Factor, which provides high sensitivity: dynamic strains as small as 0,01microstrains can be measured
- Small SG size <1mm, which makes possible to measure highly localized strains, where a foil metal SG would be too large
- Composite structures including various resistors can be fabricated in a small region of the semiconductor crystal. The monolithic structure ensures equal temperature of the resistors and by selective doping it is possible to obtain different sign of piezoresistive effect in different resistors. Therefore, it is possible to devise SG configurations where the strain effects in different resistors inserted in a Wheatstone bridge collaborate to produce a voltage output, whereas the temperature effects are compensated