# Introduction to Variable Resistance Transducers

## Strain Gauge


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# Strain Sensor

- The measurement of strain is very common in process control.
- The strain sensors are used to measure many other process variables, including flow, pressure, weight and acceleration.
- We will first review the concept of strain and how it is related to the forces that produce it, and then discuss the sensors used to measure strain.

# Strain and Stress

- **Strain** is the result of the application of forces to solid objects.
- The forces are defined in a special way described by the general term, **stress.**
- A special case exists for the relation between force applied to a solid object and the resulting deformation of the object.
- Solids are assemblages of atoms in which the atomic spacing has been adjusted to render the solid in equilibrium with all external forces acting on the object. This spacing determines the physical dimensions of the solid.
- If the applied forces are changed, the object atoms rearrange themselves again to come into equilibrium with the new set of forces. This rearrangement results in a change in physical dimensions that is referred to as a deformation of the solid.
- The effect of the applied force is referred to as a **stress** and the resulting deformation as a **strain.**

# stress-strain relationships

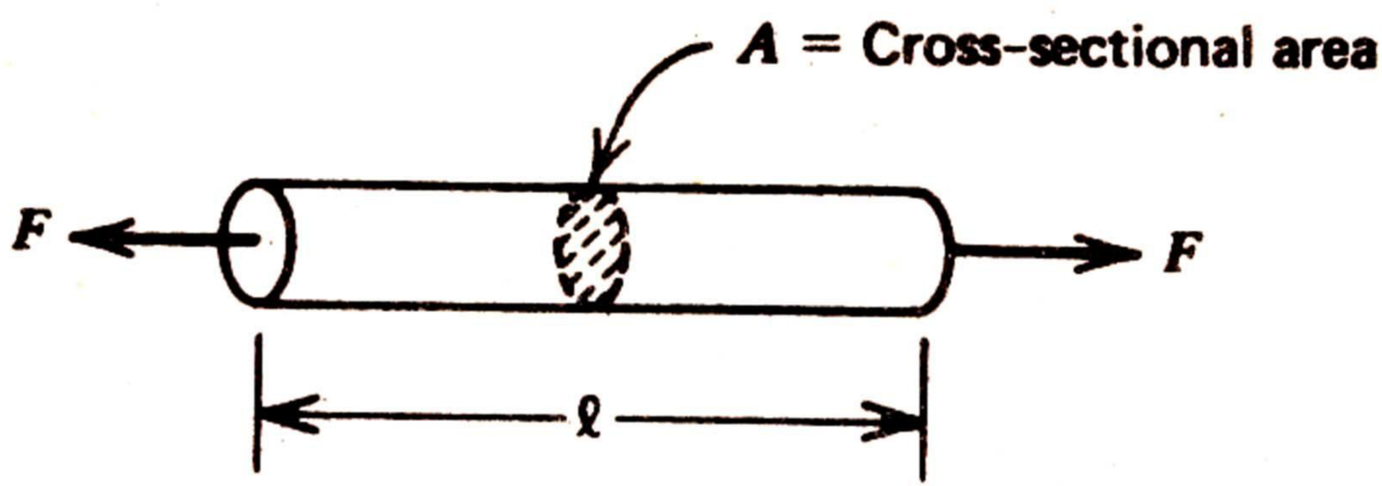
- Three most common types of stress-strain relationships.

❑ Tensile stress-strain

❑ Compressional stress-strain

❑ Shear stress-strain

## Tensile stress-strain




a) Tensile stress applied to a rod

# Contd..

- In figure, the nature of a tensile force is shown as a force applied to a sample of material so as to elongate or pull apart the sample.
- In this case, the stress is defined as

Tensile Stress= *F/A*

- Where, F= applied force in N;

A= cross-sectional area of the sample in m2.

- unit of stress is like pressure.
- The strain in this case is defined as the fractional change in length of the sample.

Tensile Strain= Δl/l

- Where, Δl = Change in length in m

l=original length in m.

- Strain is thus a unitless quantity.

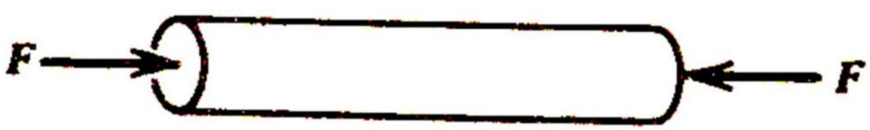
# Compressional Stress-strain

- The only differences between compressional and tensile stress are the direction of the applied force and the polarity of the change in length.
- Thus, in a compressional stress, the force compresses the sample, as shown in figure.
- The compressional stress is defined as

$$\text{Compressional stress} = F/A$$

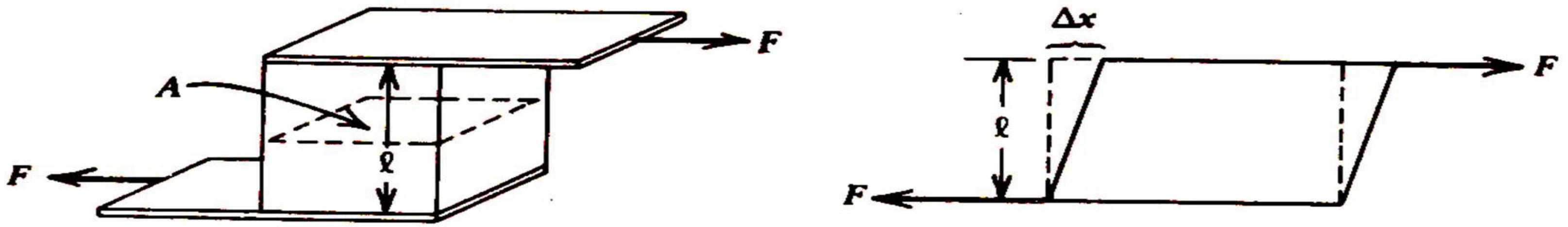
- The resulting strain is also defined as the fractional change in length but where the sample will now decrease in length.

$$\text{Compressional strain} = \Delta l/l$$




b) Compressional stress applied to a rod

# Shear stress-strain




a) Shear stress results from a force couple

b) Shear stress tends to deform an object as shown

**Figure** Shear stress is defined through the elements of this figure.

- Figure shows the nature of the shear stress.
- In this case, the force is applied as couple (that is not along the same line), tending to shear off the solid object that separates the force arms.
- In this case, the stress is again Shear stress= F/A
- Where F=force in N;

  A=cross sectional area of sheared member in m2.
- The strain in this case is defined as the fractional change in dimension of the sheared member. Shear strain= Δx/l
- Where Δx=deformation in m;

  l=width of a sample in m;

# Stress-Strain Curve

- If a specific sample is exposed to a range of applied stress and the resulting strain is measured, a graph similar to figure below

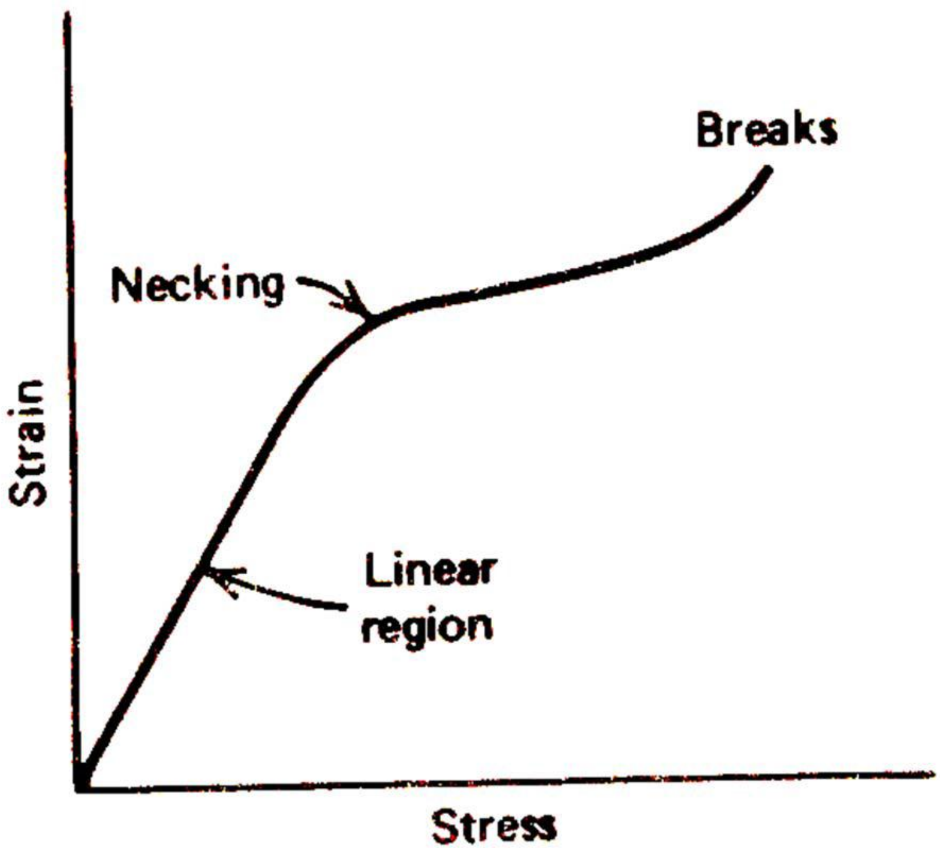


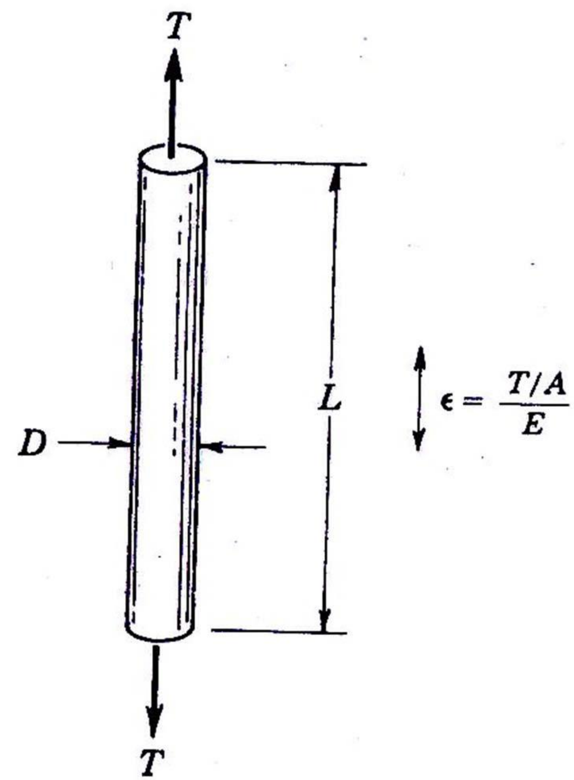

**Figure** A typical stress-strain curve showing the linear region, necking, and eventual breaking.

# Stress-Strain Curve

- This graph shows that the relationship between stress and strain is linear over some range of stress.
- If the stress is kept within the linear region, the material is essentially elastic in that if the stress is removed, the deformation is also gone.
- But if the elastic limit is exceeded, permanent deformation results.
- The material may begin to “neck” at some location and finally break.
- Within the linear region, a specific type of material will always follow the same curves, despite different physical dimensions.
- Thus, we can say that the linearity and slope are a constant of the type of material only.
- In tensile and compressional stress, this constant is called the modulus of elasticity, or Young’s modulus.

# Modulus of Elasticity

• Consider the bar as shown in figure subjected to the axial load T.
• Under no load conditions the length of the bar is L and the diameter is D.
• The cross sectional area of the bar is designated by A.



# Modulus of Elasticity

- If the load is applied such that the stress does not exceed the elastic limit of the material,
- The modulus of elasticity, or Young's modulus is given by

$$E, Y = \frac{Stress}{Strain} = \frac{T/A}{\Delta L/L}$$

- It is expressed in $N/m^2$.
- Table gives the modulus of elasticity for several materials.

**TABLE** Modulus of Elasticity

| Material | Modulus ($N/m^2$) |
|---|---|
| Aluminum | $6.89 \times 10^{10}$ |
| Copper | $11.73 \times 10^{10}$ |
| Steel | $20.70 \times 10^{10}$ |
| Polyethylene (plastic) | $3.45 \times 10^{8}$ |

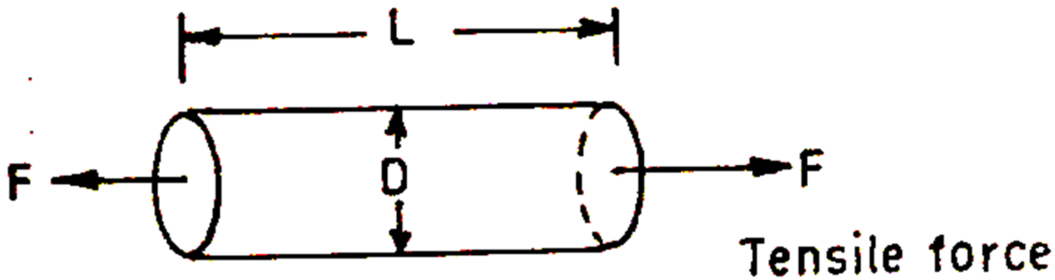
# Poisson's ratio

- Resulting from the deformation in the axial direction is a corresponding deformation in the cross-sectional area of the bar.
- The change in area is evidence by a change in the diameter or, more specially, by a change in the transverse dimension.
- The ratio of the unit strain in the transverse direction to the unit strain in the axial direction is defined as Poisson's ratio and must be determined experimentally for various materials.

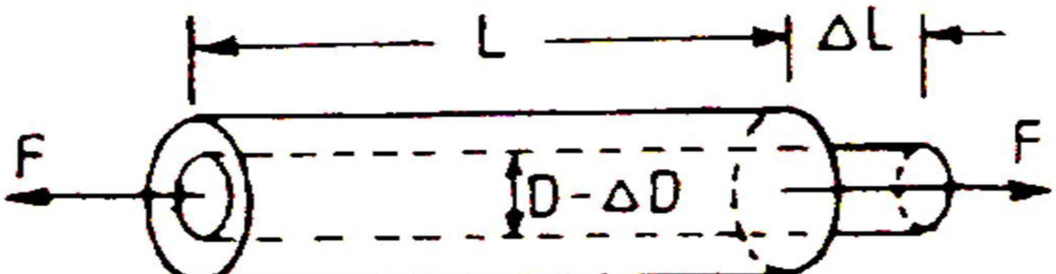
$$\gamma = -\frac{\varepsilon_t}{\varepsilon_a} = -\frac{dD/D}{dL/L}$$

# Strain gauge Principles

- Let us we have a cylindrical wire.
- Here, *L is the length of the wire and A is the cross sectional* area and *R is the radius.*




- Now, we apply a tensile force. *L is changed to dL due to action* of force in axial direction and in the lateral direction undergo reduced in size.



# Strain gauge Principles

- Hence the change in resistance

$$\frac{dR_e}{R_e} = \varepsilon(1+2\gamma) + \frac{d\rho}{\rho} \Rightarrow \frac{dR_e}{R_e} \Big/ \varepsilon = (1+2\gamma) + \frac{\frac{d\rho}{\rho}}{\varepsilon}$$

- The last term in the right hand side of the above expression, represents the change in resistivity of the material due to applied strain that occurs due to the *piezo-resistance property* of the material.
- In normal practice which is very small, we will ignore it.
- In fact, all the elements in the right hand side of the above equation are independent of the geometry of the wire, subjected to strain, but rather depend on the material property of the wire.
- Due to this reason, a term *Gage Factor is used to characterize* the performance of a strain gage.

# Gauge Factor

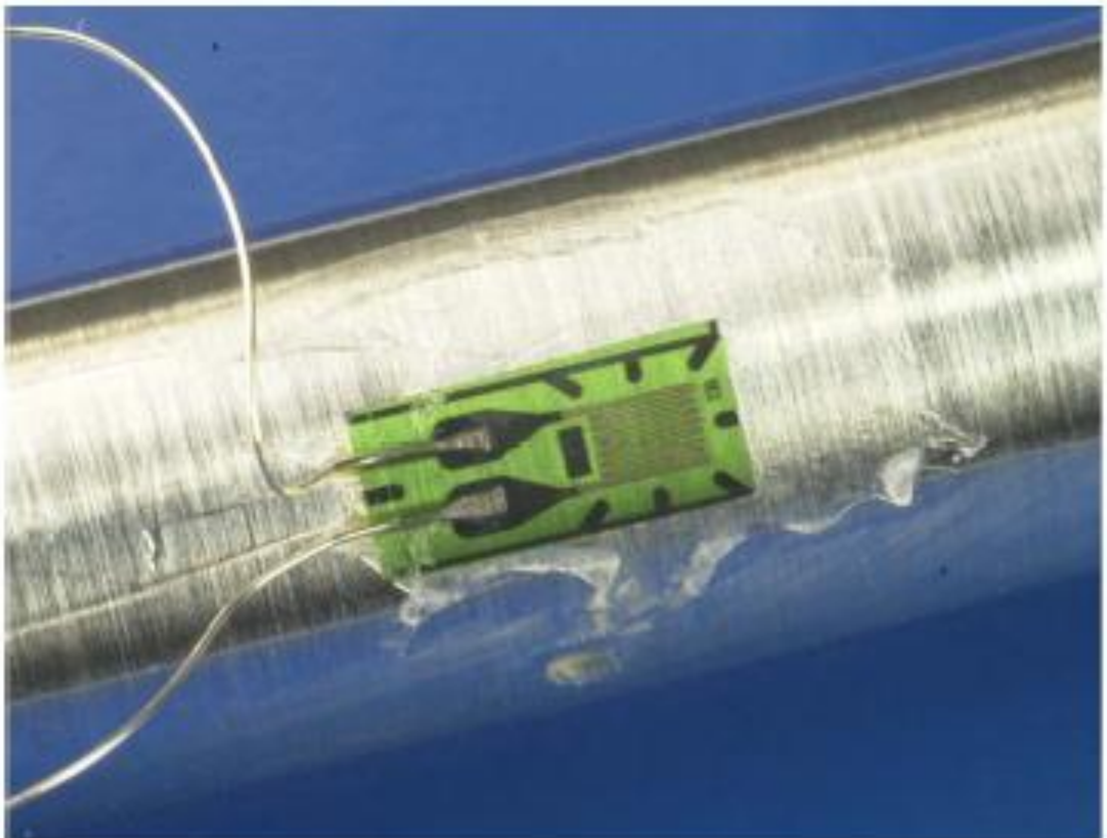
- Gauge factor is defined as

$$GF = \frac{dR_e / R_e}{dL / L} = 1 + 2\gamma = sensitivity$$

- For metal gauges, this number is always close to 2.
- For some special alloys and carbon gauges, the GF may be as large as 10.
- A high GF is desirable because it indicates a larger change in resistance for a given strain and is easier to measure.
- However, the semiconductor type strain gages have a very large Gage Factor, in the range of 100-150. This is attained due to dominant piezo-resistance property of semiconductors.
- The commercially available strain gages have certain fixed resistance values, such as, 120Ω, 350 Ω, 1000 Ω, etc.
- The manufacturer also specifies the Gage Factor and the maximum gage current to avoid self-heating (normally in the range 15 mA to 100 mA).

# How it looks?

• A strain gauge is a thin, wafer-like device that can be attached to a variety of martial to measure applied strain.



# Ideal Strain Gauge Characteristics

- High resistance
- Large change in resistance with strain
- High elastic limit
- Insensitive to temperature in both physical and electrical properties
- Linearity between resistance change and unit strain
- Very small size

# Material

- The choice of material for a metallic strain gage should depend on several factors.
- The material should have low temperature coefficient of resistance. It should also have low coefficient for thermal expansion.
- Judging from all these factors, only few alloys qualify for a commercial metallic strain gage. They are:
- *Advance (55% Cu, 45% Ni): Gage Factor between 2.0 to 2.2*
- *Nichrome (80% Ni, 20% Co): Gage Factor between 2.2 to 2.5*
- Apart from these two, *Isoelastic -another trademarked alloy* with Gage Factor around 3.5 is also in use.
- Semiconductor type strain gages, though having large Gage Factor, find limited use, because of their high sensitivity and nonlinear characteristics.

**TABLE**
**Characteristics of some resistance strain-gage materials**

| Material | Trade name | Approx. gage factor, $F$ | Approx. resistivity at 20°C, $\mu\Omega \cdot cm$ | Temp. coeff. of resistance, $°C^{-1} \times 10^6$ | Remarks |
|---|---|---|---|---|---|
| 55% Cu, 45% Ni | Advance, Constantan, Copel | 2.0 | 49 | 11 | $F$ constant over wide range of strain; low-temperature use below 360°C |
| 4% Ni, 12% Mn, 84% Cu | Manganin | 0.47 | 44 | 20 | Same |
| 80% Ni, 20% Cu | Nichrome V | 2.0 | 108 | 400 | Suitable for high-temperature use to 800°C |
| 36% Ni, 8% Cr, 0.5% Mo, 55.5% Fe | Isoelastic | 3.5 | 110 | 450 | Used for low temperatures to 300°C |
| 67% Ni, 33% Cu | Monel | 1.9 | 40 | 1900 | Useful to 750°C |
| 74% Ni, 20% Cr, 3% Al, 3% Fe | Karma | 2.4 | 125 | 20 | Useful to 750°C |
| 95% Pt, 5% Ir | — | 5.0 | 24 | 1250 | Useful to 1000°C |
| Silicon semiconductor | — | −100 to +150 | $10^9$ | 90,000 | Brittle but has high-gage factor; not suitable for large strain measurements |

# Types of Strain Gauges

The following are the major types of strain gauges:

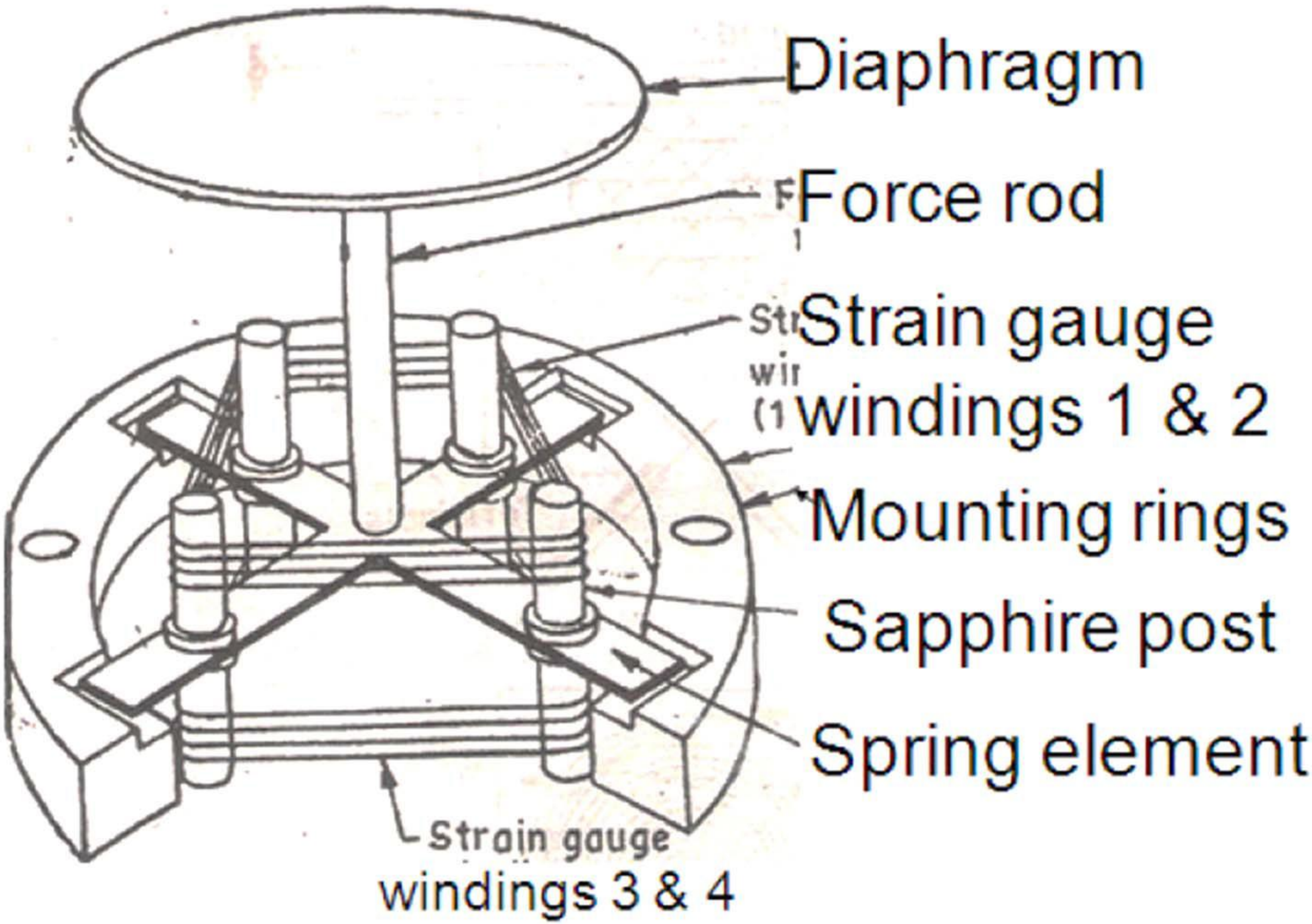
- Unbonded metal strain gauges
- Bonded metal wire stain gauges
- Bonded metal foil strain gauges
- Vacuum deposited thin metal film strain gauges
- Sputter deposited thin metal strain gauges
- Diffused metal strain gauges

Stain gauges are broadly used for two major types of applications and they are:

i) Experimental stress analysis of machines and structures.

ii) Construction of force, torque, pressure, flow and acceleration transducers.

# Unbonded metal strain gauges



# Unbonded metal strain gauges

- The gauge consists of a wire stretched between two points in an insulating medium such an air.

- The wires may be made of various copper nickel, chrome nickel or nickel iron alloys.

- They are about 0.003mm in diameter, have a gauge factor 2 to 4 and sustain a force of 2mN.

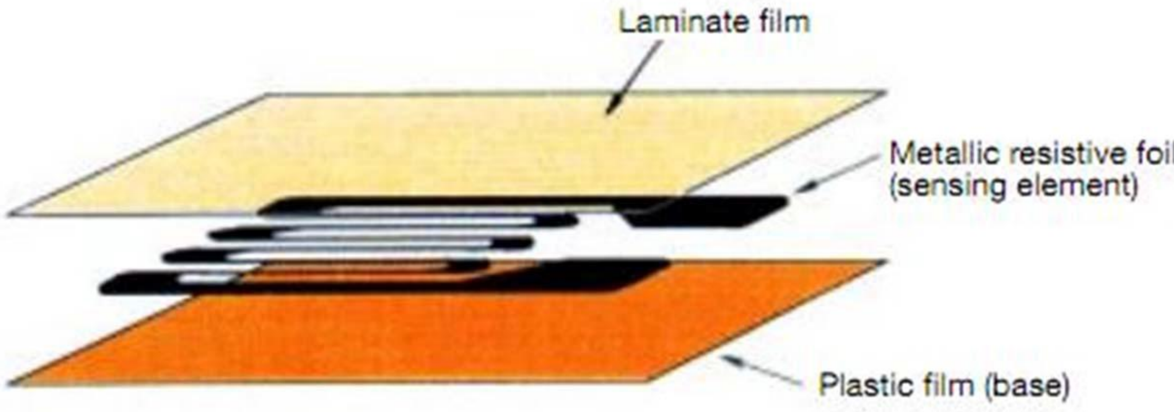
- The length of wire is 25mm or less.

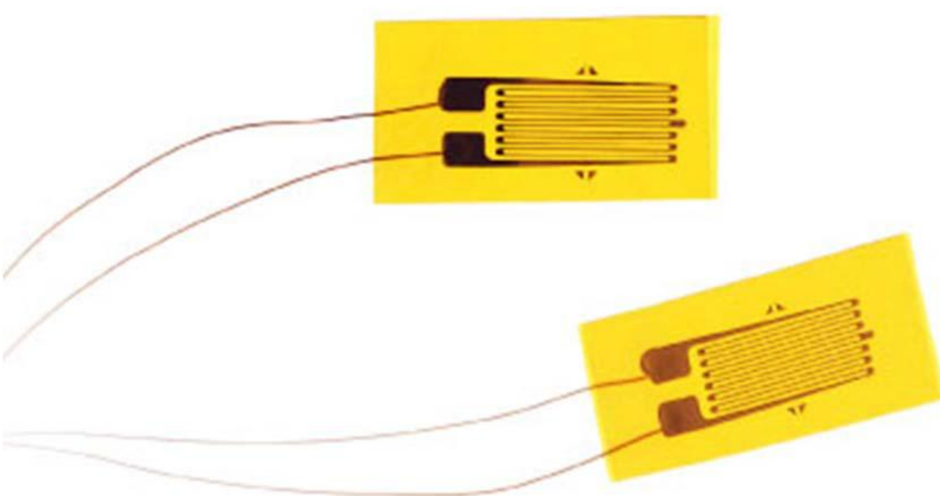
- In figure, the flexure element is connected via rod to a diaphragm which is used for sensing of pressure.

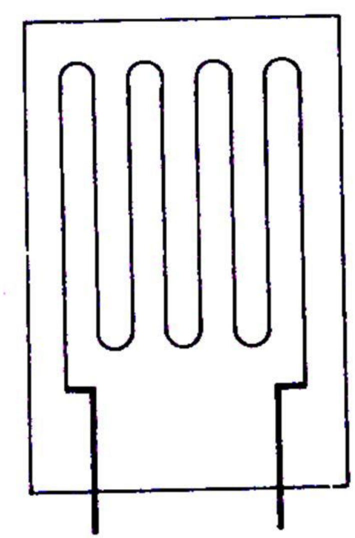
# Bonded Wire Strain Gauges

- The bonded metal-wire strain gauges are used for both stress analysis and for construction of transduces.
- A resistance strain gauge consists of a grid of fine resistance wire about 0.025mm in diameter or less.
- The grid is cemented to carrier (base) which may be a thin sheet of paper, a thin sheet of Bakelite or a sheet of Teflon.
- The wire is covered on top with sheet of material so as to prevent it from any mechanical damage.
- The carrier is bonded with a adhesive material to the specimen under study. This permits a good transfer of strain from carrier to grid of wires.
- The wires cannot buckle as they are embedded in a matrix of cement and faithfully follow both the tensile and compressive strains of the specimen.

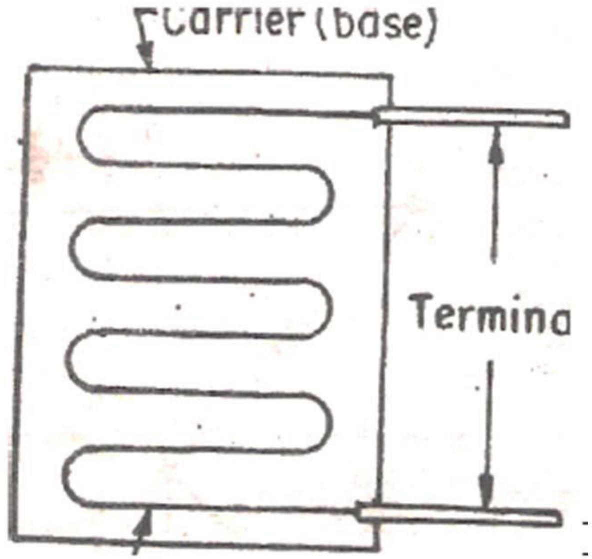
# Bonded Wire Strain Gauges



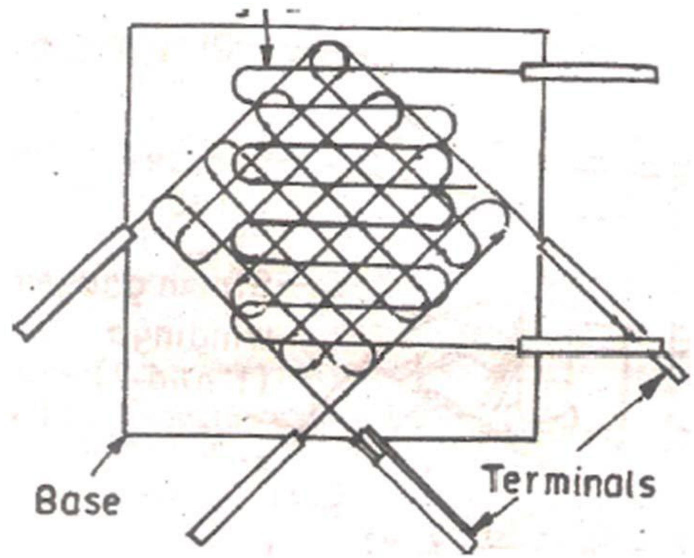





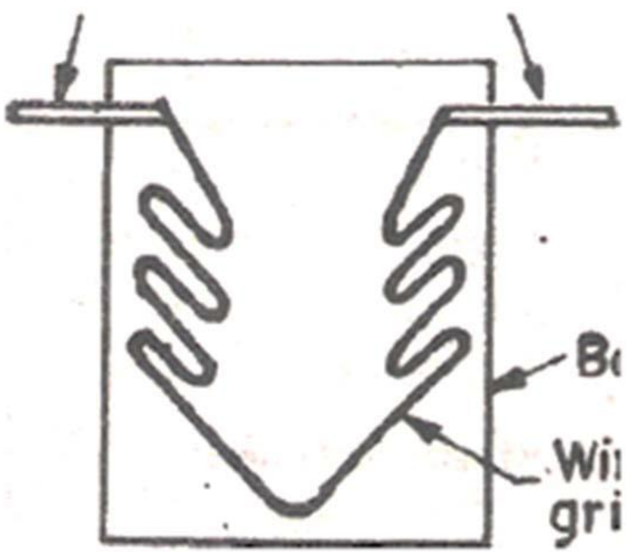
(a)



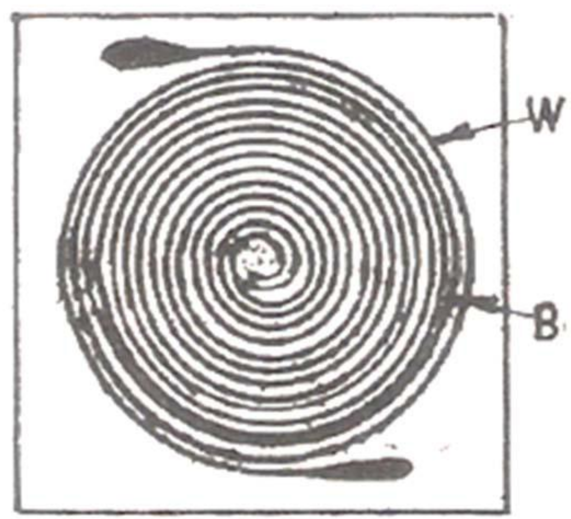

Linear Stain gauge




Rosette



Torque gauge



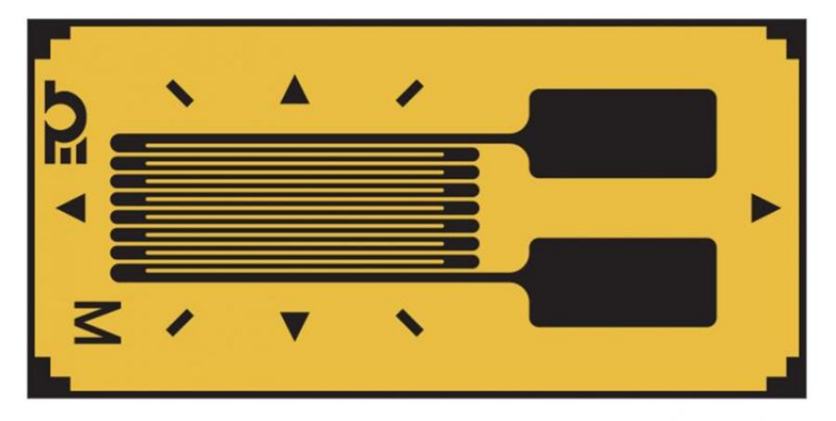

Helical gauge

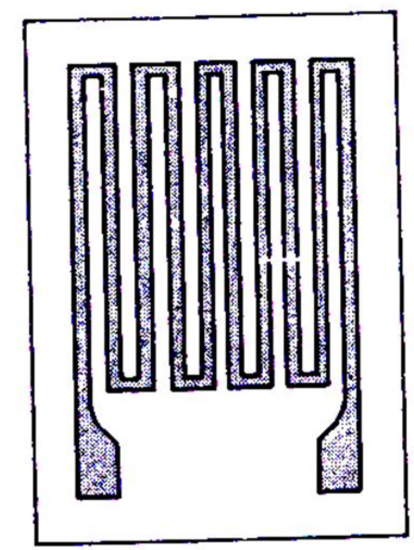
# Rosette

- The strain gage in fig. (a) can measure strain in one direction only.
- But if we want to measure the strain in two or more directions at the same point, strain gage *rosette,* which is manufactured by stacking multiple strain gages in different directions, is used.
- Fig. (b) shows a three-element strain gage rosette stacked at 450.

# Bonded Metal Foil Strain Gauges

- This class of strain gauges is only an extension of the bonded metal wire strain gauges.
- Foil type gauges have a much greater heat dissipation capacity as compared with wire wound strain gauges on account of their greater surface area for the same volume.
- For this reason, they can be used for higher operating temperature range.
- Also the large surface area leads to better bonding.





(b)

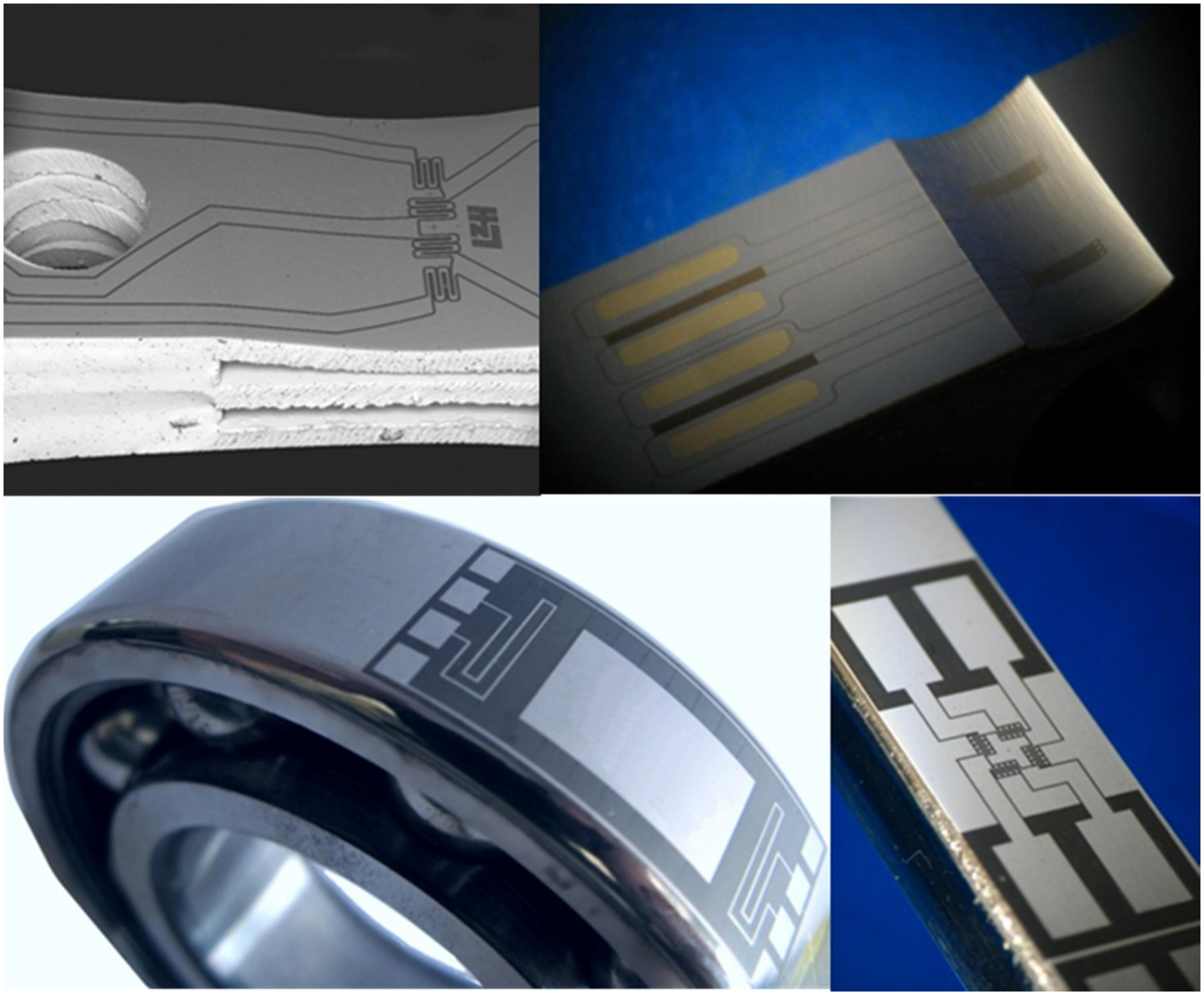
# Thin film Metal Strain Gauge

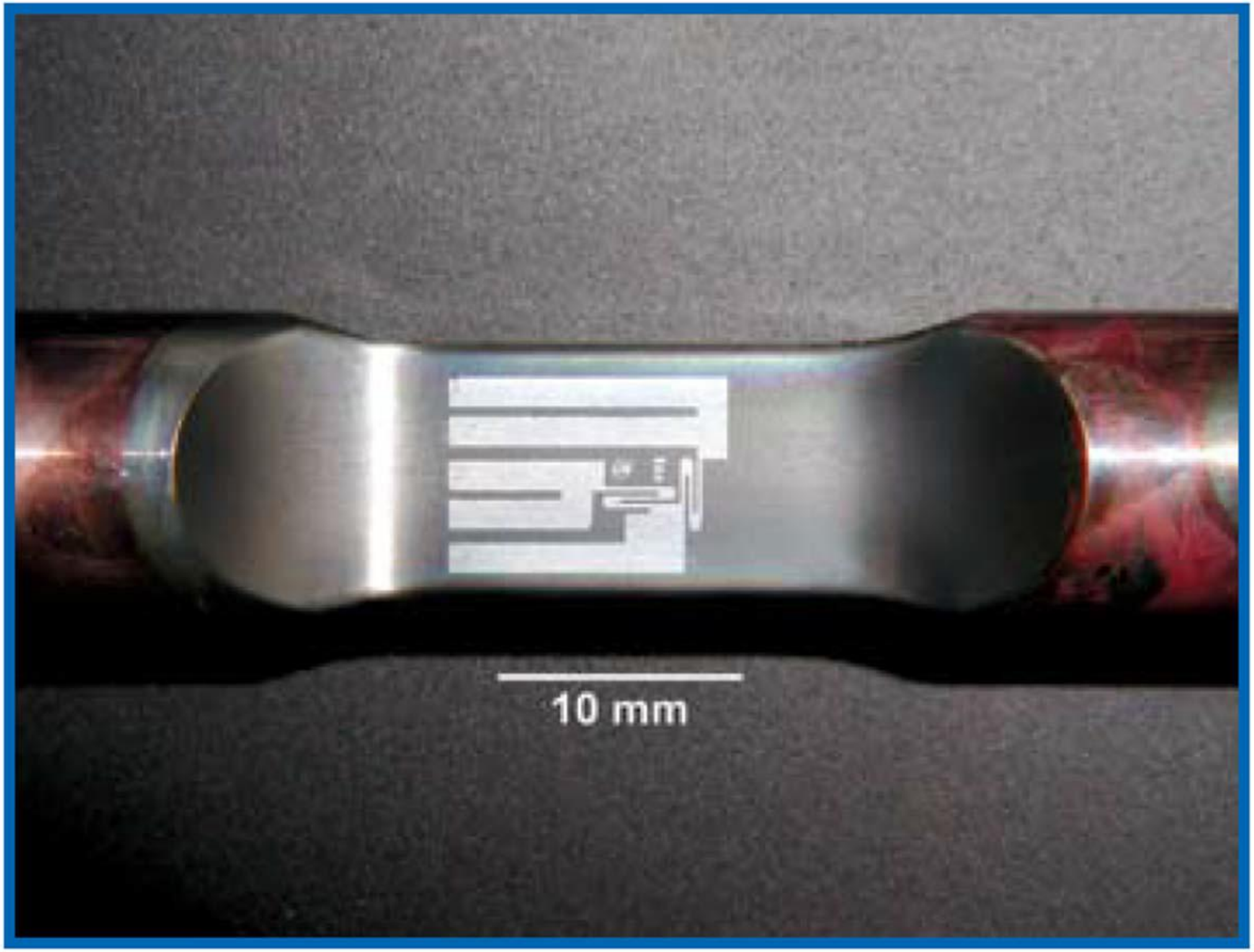
- A thin film is layer of material ranging from fractions of nanometer to several micrometer in thickness.
- A familiar application of thin films is the house hold mirror, which typically has a thin metal coating on the back of the sheet of glass to form a reflective interface.
- Same technology is used to develop thin film metal strain gauge.
- Thin-film strain gauges are produced by sputtering or evaporating thin films of metals or alloys onto the elastic element.
- The manufacture of a thin film strain gauge system will go through several stages of evaporation and sputtering and may have up to eight layers of material.
- Thin film technology is used to made this.
- Both the evaporation and sputtering processes form all the strain gauge elements directly on the strain surface, they are not separately attached as in the case of bonded strain gauges.

# Contd..

- Normally foil or wire gauge bonded onto the surface of a test Article (with glue, ceramic cement, or flame-sprayed ceramic) is widely used at low temperatures because of its simplicity, high sensitivity, reliability, and low cost.
- As the operating temperature increases; however, the problems associated with this type of gauge also increase. At higher temperatures, the gauge materials currently in use experience either oxidation or structural changes.
- As a result, the characteristics of the gauge do not remain within acceptable limits over long periods of time, nor do they vary in a predictable manner.
- In addition, the bonding agents limit both the degree of strain transmitted from the test structure to the gauge and the maximum working temperature of the gauge.
- These problems can be avoided in thin metal strain gauge.

# How it looks?






*thin-film strain gauge on a turbine engine alloy test specimen*

# Semiconductor Strain Gauge

| Material | Composition | Gauge factor | Temp. Coefficient Of Resistance($10^{-6}$/ $^{0}$C) |
|---|---|---|---|
| Constantan | 45%Ni, 55% Cu | 2.0 | 15 |
| Isoelastic | 36% Ni, 52% Fe, 8% Cr, 4%(Mn, Si,, Mo) | 3.5 | 200 |
| Karma | 74% Ni, 20% Cr, 3% Fe, 3% Al | 2.3 | 20 |
| Monel | 67% Ni, 33% Cu | 1.9 | 2000 |
| Silicon | P-type | 100 to 170 | 70 to 700 |
| Silicon | N-type | -140 to -100 | 70 to 700 |

# Semiconductor Strain Gauge

- In some applications, the sensitivity of foil gauges is not adequate to produce an acceptable stain gauge signal .
- Semiconductor (SC) strain gauges are particularly useful in such situations.
- The strain element of an SC strain gauge is made of a single crystal of piezoelectric material such as silicon, doped with a trace impurity such as boron.

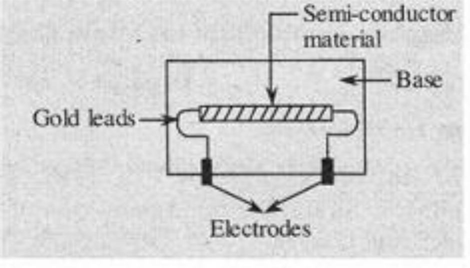


fig 4.1 Semiconductor Strain gauge

# Advantages of SC stain gauges

1. High gauge factor: This allows measurement of very small strain (3000μ strain).

2. The resistivity is also higher, providing reduced power consumption and lower heat generation.

3. Mechanical hysteresis is negligible.

# Disadvantages of SC stain gauges

1. The strain-resistance relationship is more nonlinear.

2. They are brittle and difficult to mount on curved surfaces.

3. The maximum stain that can be measured is one to two orders of magnitude smaller (typically, less than 0.001m/m)

4. They are more costly.

5. They have much larger temperature sensitivity.

# Some Characteristics

There are two types of semiconductor strain gauges:

- P-type: which are made of silicon doped with an accepter impurity. In p-type strain gauges, the element produces a positive change in resistance in response to a positive strain.
- N-type: which are made of a semiconductor doped with a donor impurity (e. g. arsenic). In n-type strain gauges, the element responds with a negative change in resistance to a positive strain.