STRAIN SENSORS

In recent years the area of sensors has become increasingly important because of their varied applications in many areas. The term sensor is a broad terminology which encompasses a wide variety of devices. The present article deals with one

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such type of sensor, namely the strain sensor. The alternative term commonly used for strain sensor is strain gauge. Basically, a strain gauge is a device used to measure the linear deformation (mechanical surface strain) occurring in a material during loading. In addition to their fundamental use for measuring strains as such, strain gauges are also used for measuring other physical quantities such as pressure, load, displacement, torque, and so on by employing them as sensors in other measuring systems.

Historically (1), the development of strain gauges has followed different paths, and gauges have been developed based on electrical, mechanical, optical, acoustical, and pneumatic principles. Among these, the electrical strain gauges have become so widely accepted that they now dominate the entire strain gauge field except for a few special applications. In its widest sense, the electrical strain gauge includes many varieties, utilizing the full range of electrical quantities, that is, resistance, reluctance, capacitance, inductance, and others. However, over the years the electrical resistance type strain gauge has become the most widely used device, and this is what is usually meant when the term strain gauge is used. In this article, the term strain gauge refers to the electrical resistance type strain gauge.

ORIGIN OF STRAIN GAUGES

The origin (1) of the strain gauge goes back to Robert Hooke (1635–1703) whose famous law states that, within certain limits, stress is proportional to strain. Later, Robert Young (1773–1829) provided a quantitative relation between stress and strain in a bar under simple tension (or compression) by his modulus of elasticity equation,

$$\sigma = E \times \epsilon \tag{1}$$

Where E is the modulus of elasticity σ the stress and ϵ is the strain.

Poisson (1781–1840), a French mathematician, extended the laws of elasticity from uniaxial to two- and three-dimensional aspects which involved another well known material constant, now named Poisson's ratio. Although mathematicians of the last two centuries worked out a great deal of theory, it is comparatively only at a later stage that strain measurement has been done on a large scale. This situation undoubtedly is because of the difficulty of making precise quantitative measurements on metals whose elastic strains are extremely small.

CONCEPT OF STRESS AND STRAIN

All bodies can more or less be deformed by suitably applied forces. As a result of this, forces of reaction come into play internally. This is due to the relative displacement of its molecules. This tends to balance the load and restore the body to its original condition. The restoring or recovering force per until area set up inside the body is called stress. The deformation or the change produced in the dimension of a body under the action of external forces is called strain. It is measured by the change per unit length (linear strain), per unit volume (volume strain), or the angular deformation (shear strain) depending on whether the change is along its length, volume, or the shape of the body.

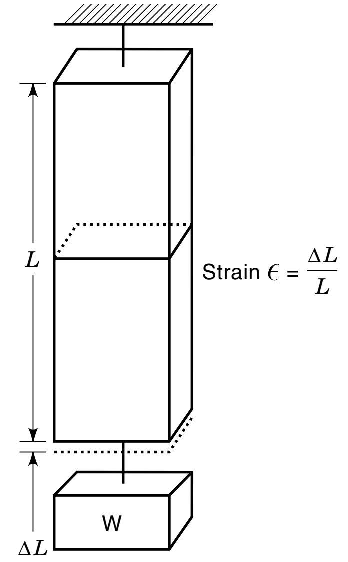

Figure 1. Schematic of the bar subjected to load.

If a bar of length L is subjected to a direct load W (Fig. 1), and the resulting change in length of the bar is ΔL, then the strain produced is given by Ref. 2

$$\text{Strain } (\epsilon) = \frac{\text{Change in length}}{\text{Original length}} = \frac{\Delta L}{L} \tag{2}$$

Strain is thus a measure of the deformation of the material and is nondimensional; it is simply a ratio of two quantities with the same unit. In practice, the extension of materials under load are very small. Hence it is convenient to measure strain in units of 10^{-6} that is, microstrain ($\mu\epsilon$).

BASIC OPERATING PRINCIPLE OF THE STRAIN GAUGE

The discovery of the basic operating principle (3) of the strain gauge dates back to 1856, when Lord Kelvin reported that certain metallic conductors subjected to mechanical strain exhibited a corresponding proportional change in electrical resistance. This property, namely change in resistance due to strain, is referred to as the piezoresistive effect. Generally the term *piezoresistive effect* is used in connection with semiconducting materials.

STRAIN SENSITIVITY/GAUGE FACTOR

In general, all electrically conducting materials possess strain sensitivity. The dimensionless number F is variously termed the electrical resistance–strain coefficient, the strain sensitivity factor, or the gauge factor and is expressed mathematically (3,4) as,

$$F = \frac{\Delta R/R}{\Delta L/L} \tag{3}$$

$$\text{since } \frac{\Delta L}{L} = \epsilon,$$

$$F = \frac{\Delta R/R}{\epsilon} \tag{4}$$

where R and L represent, respectively, the initial resistance and length, while ΔR and ΔL represent the small changes in resistance and length which occur as the gauge is strained. The gauge factor of a strain gauge is thus an index of the strain sensitivity of the gauge. The higher the gauge factor, the more sensitive the gauge and the greater the electrical output for indication or recording purposes.

The major milestones/events in the history of strain gauge development are indicated in Appendix 1.

FEATURES OF AN IDEAL STRAIN GAUGE

An ideal strain gauge should possess the following characteristics. It should:

- Have high strain sensitivity (gauge factor)
- Exhibit linear response to strain
- Have a very low temperature coefficient of resistance (TCR)
- Be insensitive to humidity and other ambient conditions likely to be encountered
- Have good temporal stability
- Be suitable for use as the sensor in other transducer systems where an unknown quantity is measured in terms of strain
- Have low hysteresis effect

Although in practice it is difficult to meet all the requirements of an ideal strain gauge, a great deal of effort has been expended making a strain gauge having the characteristics close to that of an ideal one.

GENERAL CLASSES OF STRAIN GAUGES

Broadly the types of strain gauges developed over the years are

- Unbonded—wire gauges
- Bonded—wire gauges
- Bonded—foil gauges
- Semiconductor gauges
- Thin film strain gauges

The unbonded wire strain gauge consists of a strain-sensitive wire mounted on a mechanical frame whose parts can have slight movement with respect to each other. This relative movement causes a change in tension of the wire resulting in a change in electrical resistance. The electrical resistance change produced is a measure of the relative displacement or strain. This type of gauge can be made of entirely inorganic and high temperature materials, so that operation of such sensors is possible even in high dose radiation and high temperature environments.

The bonded wire/foil strain gauge also consists of a strain-sensitive wire or foil, but is entirely attached by an adhesive to the member (component) whose strain is to be measured. As the strain-sensitive wire or foil are basically electrically conducting, they have to be electrically isolated from the component (especially if the component is made of conducting material). Usually the required level of electrical insulation in these gauges is provided by the adhesive and/or insulating backing material. The commonly used adhesive and backing materials are of the phenolic or epoxy resin type, some of which may resist the use of the bonded gauges in radiation and very high temperature environments. Also, as the adhesive and backing material are in the force path, the accuracy of measurement is limited by the characteristics of these materials. Normally the force required to produce the displacement in bonded wire/foil type gauges is larger than that required in the case of an unbonded wire gauge because of the additional stiffness of the member. The bonded wire/foil type gauge can operate in tension, compression, or bending mode. Bonded foil type strain gauge is a by-product of precisely photo-etched printed electronic circuits by photolithography process. Foil gauges have undergone intensive development and are available in many grid configurations (Fig. 2) and a variety of different foil alloys. Foil gauges are thinner than wire gauges. It is easier to make complicated grid designs with these gauges and they conform more easily to curved surface components.

Generally, wire or foil type gauges made of metal and metal alloys exhibit a gauge factor value typically about 2.0 to 5.0. They are basically low signal devices and require signal amplification. Although their signal output is small, their linearity and hysteresis characteristics are generally good.

Semiconductor gauge development resulted from the intensive research in solid-state physics relating to semiconductors. Semiconductor gauges offer higher sensitivity than wire and foil type gauges. By controlling the type and amount of dopant in the semiconductor material, the strain gauge properties can be controlled effectively making them suitable for specific applications. In the case of semiconductor gauges, gauge factors of about 10 to 120 are typical, either positive or negative. Although the gauge factor values are numerically large, they are not linear and greatly affected by temperature variations above 70°C. However, because of their high sensitivity they are attractive for detecting very small strains.

As indicated earlier, the resistance change due to strain in the case of semiconductors is generally referred to as the piezoresistive effect. On the other hand, piezoelectric type strain sensors convert mechanical strain into electrical output and are based on the piezoelectric effect observed in certain nonmetallic and insulating dielectric compounds. However, these types of strain sensors are not usually preferred for static strain measurements. In cases of strain monitoring over a prolonged period of time, better accuracy and stability can be achieved with strain gauges made of metallic alloy materials.

An important development in the field of strain gauge technology is the introduction of thin film strain gauges (5). These gauges can be made of any desirable resistor metal,

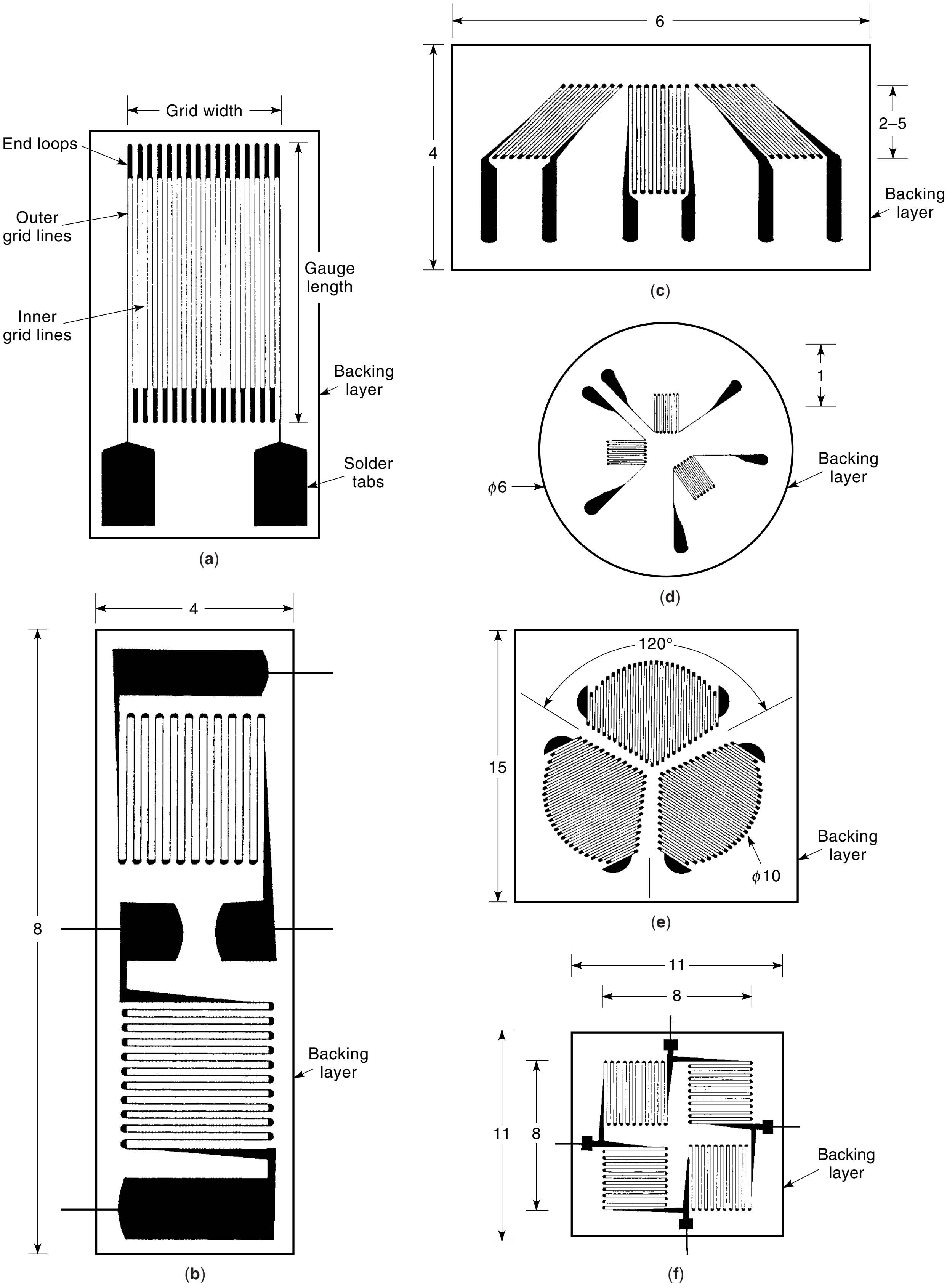

Figure 2. Foil type strain gauge configurations. (a) Single element. (b) Two element. (c), (d), (e) Three elements. (f) Four elements. Note: (1) All dimensions are in mm; (2) backing layer thickness 0.010 mm to 0.020 mm; (3) grid dimensions vary according to the type of gauge and application.

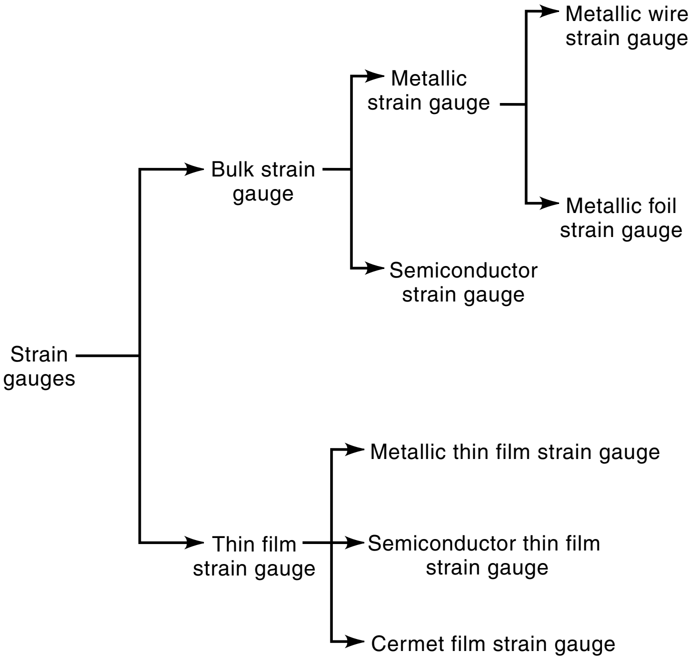

Figure 3. Broad classification of strain gauges.

metal alloy, semiconductor, or a combination of metal and dielectric (called cermets which are basically metal-dielectric composites). Thin film strain gauges are prepared mainly by vacuum deposition processes. These techniques provide the greatest flexibility to control the major strain gauge properties. It is possible to optimize specific properties by controlling the deposition conditions such as pressure, temperature, rate of deposition, and so on. Significant research has been reported in the literature regarding the evaluation of the strain gauge properties of various materials in thin film form. The extensive effort in this direction resulted in the development of special alloy/cermet films which exhibit the necessary stability, gauge factor, and resistance characteristics. Figure 3 shows the broad classification (6,7) of the strain gauges.

STRAIN SENSITIVITY DEPENDENCE

In order to have an idea of how the strain sensitivity of the material depends on other basic parameters (7), we can consider a conductor of uniform cross-sectional area A and length L, made of a material with resistivity ρ. The resistance of such a conductor is given by

$$R = \frac{\rho L}{A} \tag{5}$$

Considering all the parameters in this equation as variables, if we differentiate and substitute in the equation for gauge factor, we obtain (after simplification),

$$F = \frac{\Delta R/R}{\Delta L/L} = [1 + 2v] + \left[\frac{\Delta\rho/\rho}{\Delta L/L}\right] \tag{6}$$

Table 1. Strain Sensitivity of Various Materials (From Ref. 4)

Material	Trade Name	Typical Strain Sensitivity
Copper–nickel(55–45)	Constantan Advance	+2.1
Nickel–chromium(80–20)	Nichrome V	+2.2
Nickel–chromium(75–20) plus iron & aluminium	Karma	+2.1
Iron–chromium–aluminium (70–20–10)	Armour D	+2.2
Nickel–chromium–iron –molybdenum (36–8–55.5–0.5)	Isoelastic	+3.5
Platinum–tungsten(92–8)	—	+4.0
Copper–nickel–manganese (84–4–12)	Manganin	+0.6
Nickel	—	−12.0
Iron	—	+4.0

Where ν is the Poisson's ratio of the material. In Eq. (6), the term $(1 + 2\nu)$ represents purely a geometrical effect of deformation. The term $(\Delta\rho/\rho)/(\Delta L/L)$ represents a physical effect, namely the change in specific resistance with elastic strain (which is related to number and mobility of free electrons). In fact, in metals the dimensional change (or the geometrical effect) is the major factor, whereas in semiconductors the resistivity change is predominant. Vacuum deposited thin film materials may have additional contributions to their resistivity terms, because their structure (especially grain size and separation of grains) can be significantly different from that of the common bulk material specimens.

It is important to bear in mind that a high gauge factor is not the only criterion for selecting a suitable material for fabrication of strain gauges. In addition, the material must also possess low TCR values and exhibit excellent thermal and temperature stability. The data on the strain sensitivity of commonly used strain gauge materials (metals and alloys) are provided in Table 1. Table 2 contains data of different classes of thin film materials relevant to strain gauges.

USE OF THE WHEATSTONE BRIDGE

The Wheatstone bridge is one of the most common configurations used with strain gauges. This is because the resistance change of strain gauge is very small, and precise instrumen-

Table 2. Various Classes of Thin Film Materials and Their Characteristics Relevant to Strain Gauges (From Ref. 8)

Type and Class Film Material	Gauge Factor F	Temperature Coefficient of F (ppm/K)	Thermal Stability
Continuous, metals	2	400	Fair
Discontinuous, metals	Up to 100	∼−1000	Poor
Continuous, metal alloys	2	∼100	Good
Discontinuous, metal alloys	Up to 100	∼1000	Poor
Cermets	Up to 100	200–1000	Generally Good
Semiconductors	Up to 100	∼−1500	Good in some cases

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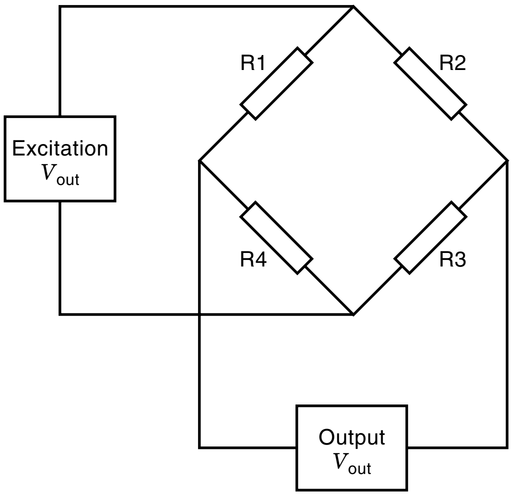


Figure 4. Wheatstone bridge configuration.

tation is required to measure it accurately. Figure 4 shows the Wheatstone bridge in its simplest form. The condition for bridge balance is,

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \tag{7}$$

Any change in resistance of the arms will unbalance the bridge and produce a voltage V_{out} across the output terminals. In strain gauge related instrumentation, usually each arm of the bridge is used as a transducer or strain gauge. The general output Eq. (4) used in these cases is the following.

$$V_{out} = \frac{F\epsilon N V_{in}}{4} \tag{8}$$

where

F = Gauge factor
V_{in} = Bridge input voltage
ϵ = Strain
N = Number of active arms of the bridge

The bridge output V_{out} obtained can be suitably amplified and processed. Details on bridge output voltage measurement, variations of wheatstone bridge configurations, bridge excitation, and associated aspects can be seen in Refs. 3, 4, 6, and 9–14.

Temperature Effects

Temperature is an important interfering input for strain gauges since resistance of strain gauges changes with both strain and temperature. Also, the material on to which the strain gauges are bonded/deposited will expand or contract with change in temperature. This causes an additional error resulting in apparent strain. Therefore, in order to carry out accurate strain measurements, temperature compensation must be employed. Several methods are available to compensate for temperature effects. One such method is to use a dummy gauge which is identical to the active gauge (in the Wheatstone bridge configuration) bonded/deposited on to a piece of similar material maintained at the same temperature. The dummy gauge and active gauge are placed in adjacent arms of the Wheatstone bridge, so that the resistance change due to the temperature and differential thermal expansion will have no influence on the bridge output voltage. Although in theory this is a simple and effective way of compensating, in practice because of inevitable differences from gauge to gauge and the fact that temperature of strain sensors is never precisely the same the inference is that it is possible to achieve superior performance with strain gauges having very low temperature co-efficient of resistance. It is important to note that, for the purpose of achieving very low temperature co-efficient of resistance for the strain gauges, thin film materials technology offers greater flexibility.

Another approach of temperature compensation involves the use of special gauges whose thermal properties are matched to the particular materials on which they are to be mounted—called self-temperature compensated (STC) gauges. STC gauges include those gauges made up of two parts; one with positive response to temperature and the other having negative response, and are so proportioned that the positive and negative responses essentially cancel each other over a given temperature range. STC gauges also include single element gauges made of various metallic or alloy materials which have been classified according to their temperature characteristics. Another variation of STC gauges is to produce a sensing element alloy which, when subjected to certain heat treatment and mechanical processing, will match the properties of the material on which the gauges are to be used.

For several applications the STC gauges are adequate and save the cost of an additional gauge and its associated installation and wiring. In situations when self compensation is not good enough, for example at higher temperatures, the bridge compensation with external compensation network approach can be employed. Detailed information on temperature compensation can be found in Refs. 3, 4, 6, 9, and 13–18.

Transverse Sensitivity

Ideally, a strain gauge should respond to strains of a specimen along a specific direction. But most strain gauges exhibit some degree of sensitivity to strains along directions other than the one to be measured. The transverse sensitivity of strain gauges refers to the behavior of gauges in responding to strains which are perpendicular to the primary sensing axis of the gauges. Normally, strain gauges have very low response to transverse strains. Therefore, the errors in strain measurement due to transverse sensitivity of strain gauges are generally quite small. However, if utmost accuracy in strain measurement is needed, then transverse sensitivity of the gauges must be taken into account. Also, the effects of transverse sensitivity should necessarily be considered in the experimental stress analysis of a biaxial stress field using strain gauges.

In fact, one of the important aspects of strain gauge technology is that in many applications both the magnitude and direction of the strain need to be measured. In such cases, the information on the directional sensitivity (both longitudinal and transverse sensitivity) of the gauges will be very helpful. More detailed aspects of transverse sensitivity (including the mathematical formula) and related information can be found in Refs. 3, 4, 19, and 20.

THIN FILM TECHNOLOGY FOR STRAIN GAUGES AND STRAIN GAUGE BASED SENSOR DEVELOPMENT

Although foil gauges are being used widely, in recent years thin film strain gauges and thin film strain gauge based transducers are gaining increasing popularity because of their several distinct advantages (1,21,22). Some of the important advantages (in comparison with the bonded foil/wire gauges) are, (1) elimination of the glue between the strain gauge and the straining member, (2) easier thermal compensation with minimal interference with the mechanical properties of the component material, (3) larger operating temperature range, (4) mass production with considerable cost reduction, and (5) complete freedom from external strain gauge suppliers. During the last decade, a number of companies have started adopting thin films technology for strain gauge transducers development. This clearly indicates that thin film techniques will play a leading role in strain gauge based device technology.

In view of this, a concise description of thin film deposition techniques is given next.

Thin films can be deposited by a variety of methods (23–27). The important techniques commonly employed (useful for strain sensors development) may be broadly classified into two categories, namely, physical vapor deposition and chemical deposition methods.

PHYSICAL VAPOR DEPOSITION

The term physical vapor deposition denotes those vacuum deposition processes such as evaporation and sputtering where the coating material is passed in to vapor transport phase by physical mechanisms, that is, evaporation, sublimation, or ion bombardment.

Thermal Evaporation

In thermal evaporation, the material to be deposited (evaporant) and the substrates on which it is to be coated are placed in vacuum. The evaporant is loaded in a heating element. The required vaporization temperature is achieved by resistance heating of the filament or boat, which conducts heat to the evaporant. At that point, the material evaporates and coats everything in its vicinity. The subsequent condensation process, consisting of nucleation and film formation, is strongly dependent on the thermal energy, the rate of arrival and the incident angle of the vapor particles, as well as the physical, chemical, and thermal conditions of the receiving surface. The resistance heating approach is a very convenient method and is widely used.

E-beam Evaporation

Some materials cannot be used as evaporants as they have high melting points or because they will react with any material used to support them in the chamber, making the deposited coating impure. Many of these materials, however, can be evaporated from an electron beam gun. In E-beam evaporation (28), the material is heated by electron bombardment. By controlling the kinetic energy of the electron beam, the depth of the melt area can be controlled. As a result, the molten evaporant material does not come into contact and alloy with the crucible (supporting material). Scanning the E-beam over the surface of the melt prevents the nonuniform deposition that would otherwise occur due to the formation of cavity in a molten source. A schematic of the general vacuum evaporation system is shown in Fig. 5.

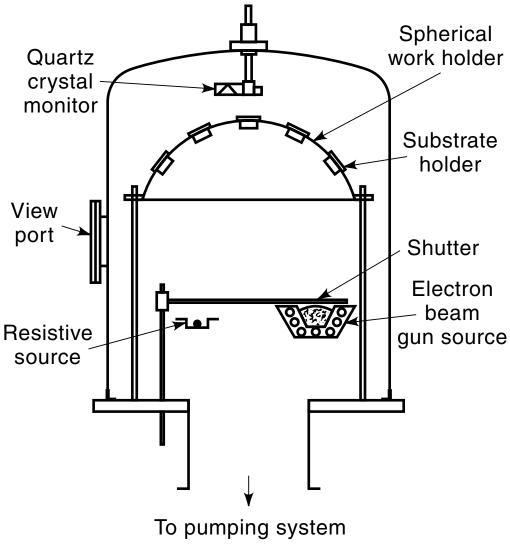


Figure 5. A schematic of the general vacuum evaporation system.

Flash Evaporation

If the evaporant is not a pure element, it will fractionate upon heating. This makes it difficult to control the stoichiometry of the deposited film. In such situations, flash evaporation, in which a fine-sized powder of the alloy is dropped at a controlled rate on to a hot ‘boat’, is employed. The temperature of the boat is held well above the minimum vaporization temperature of the individual elements of the alloy; thus the arriving powder grain instantly flashes off (totally vaporizing) without fractionation.

Sputtering

Besides thermal and E-beam evaporation, vapor species may also be created by knocking out the atoms or molecules from the surface of a solid material by bombarding it with energetic ions. The ejection process, known as sputtering, occurs as a result of momentum transfer between the impinging ions and the atoms of the target being bombarded. The sputtered species can be condensed on a substrate to form a thin film. Many different materials (including alloys or compounds) can be sputtered.

Ions for sputtering may be produced by establishing a glow discharge between the target and the substrate holder. This is referred to as glow-discharge sputtering. However, in case of ion-beam sputtering, a separate ion source is utilized. Depending on the geometry of the target-substrate system and the mode of ion transport, a large number of sputtering variants have been developed (29,30). These are briefly discussed next.

Direct Current (dc) Diode Sputtering

In this arrangement, a plasma discharge is maintained between the anode (substrate) and the cathode (target). The chamber is evacuated to about 10^{-6} torr and then backfilled to the sputtering pressure with an inert gas, usually argon. A potential applied to the electrodes gives enough energy to the electrons to ionize the argon molecules, creating a plasma. The ions in the plasma near the cathode get accelerated across the potential drop of the cathode dark space, and hit the target with enough energy to eject target atoms. These target atoms spray in all directions and coat everything in their path, including the substrates. There are three factors that characterize dc sputtering with planar diode arrangment: (1) the cathode current densities and sputtering rate are low, (2) the working pressures are high, and (3) the substrates are in contact with the plasma. A schematic of the dc diode sputtering system is shown in Fig. 6.

If the partial pressure of contaminants is higher than about 10^{-5} torr, sputtering can still be induced but the deposited films will be less pure. Oxygen, nitrogen, water vapor, and other constituents of the background gas will be incorporated in the films as they are deposited. If the base pressure is low and argon is pure, the only gas present will be argon. Very little argon will be incorporated in the films, however, because argon, as an inert element, has a low sticking coefficient. Any incorporated argon will not form compounds with the target atoms. It is also unlikely that it will alter the properties of the deposited films to any great extent.

In a diode system, bombarding ion current density and bombarding ion energy cannot be varied independently because they both depend on the cathode potential. This inflexibility occasionally presents a problem. This problem can be overcome by using a triode system.

Triode Sputtering

In this configuration, sputtering rates are increased by supplying auxiliary electrons from a thermionically emitting filament. Both the total ionization and the ionization efficiencies are increased by accelerating the electrons by means of a third electrode and injecting them into the plasma. Consequently, triode sputtering system can be operated at low pressures. With this arrangement, the bombarding ion current density and the bombarding ion energy can be varied independently. The bombarding ion current density (the plasma density) can be adjusted by varying either the temperature of the thermionic cathode or the anode potential, whereas the bombarding ion energy can be adjusted by varying the negative potential on the target (Cathode).

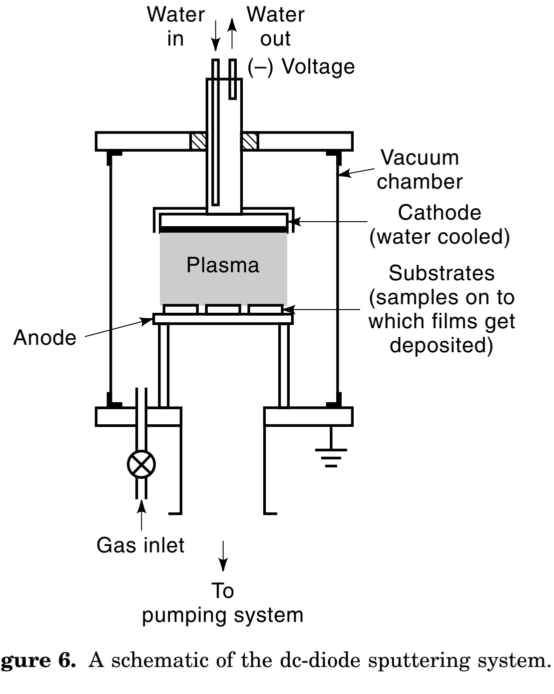


Figure 6. A schematic of the dc-diode sputtering system.

Magnetron Sputtering

In magnetron sputtering system, the ionization efficiency of the electrons is increased by increasing their path length by applying a transverse magnetic field normal to the electric field. Magnetron sputtering makes it possible to utilize the cathode discharge power very efficiently to generate high current densities at relatively low voltages and lower operating pressure to yield deposition rates which are higher than those in the nonmagnetron sputtering systems.

BIAS SPUTTERING

The term *bias sputtering* is used to refer to the specific process of maintaining a negative bias on substrates during sputter deposition. In this case, the film is subjected to steady ion bombardment throughout its growth, which effectively cleans the film of adsorbed gases otherwise trapped in it as impurities.

Radio Frequency Sputtering

Direct current methods cannot be used to sputter insulating targets due to the buildup of positively charged sputtering gas ions which repel the bombarding (sputtering) ions. This difficulty can be overcome by using radio frequency (RF) sputtering. In RF sputtering a high frequency alternating potential is used to neutralize surface charges periodically. RF sputtering apparatus can be used to deposit conducting, semiconducting, and insulating films. Therefore RF sputtering has found wide applications.

Ion Beam Sputtering/Deposition

This is a relatively newer technique. Ion beam sputtering permits independent control over the energy and current density of the bombarding ions. Ion beams are used for thin film deposition in a variety of configurations (31). Compared with other thin film deposition techniques, ion beams provide a controlled, collimated flux of energetic particles that may be directed at the substrate, a target material, or a growing film.

Ion Plating

Ion plating is the result of the combination of vacuum evaporation and sputtering. In this arrangement, the source of evaporation is placed in a vacuum chamber. Opposite to this source is placed a substrate holder. The high voltage applied to the substrate generates a discharge (plasma). When the evaporation source emits vapors, the vapor passes through a glow discharge on its way to the substrates. Ion plating technique combines certain advantages of both evaporation and sputtering.

CHEMICAL METHODS

Electrodeposition and chemical vapor deposition are the two important techniques that come under this category. These methods have a limited and specific usage. Chemical methods (32) require simple equipment, and thus may be more economical. These methods, however, are often complex and difficult to control. Also, some of these techniques demand that the supporting substrate withstand high temperature; others require that substrates be exposed to various solvents. A brief description of these methods is given next.

Electrodeposition is done in three ways, namely, electrolytic deposition, electroless deposition, and anodization. In the electrolytic deposition, two electrodes and a suitable electrolyte to pass a current are required. The deposition rate is dependent on the temperature of the electrolyte and the geometry of the cathode including other parameters.

In electroless deposition, the external potential source is replaced by a chemical reduction process. The deposition rate is highly affected by the temperature of the reaction which is rather difficult to control.

The production of a coating of metal oxide or metal hydroxide by the electrochemical oxidation of a metal anode in an electrolyte is called anodization. It is achieved by maintaining constant current or constant voltage. The sticking of oxide films on the parent metal depends on the nature of the metal. These metals are often referred to as “valve metals” because of rectifying characteristics of their anodic oxides. The anodic films are invariably amorphous in nature, but crystalline structure may be obtained by suitably adjusting the conditions of anodization.

Chemical Vapor Deposition (CVD)

In this method, a volatile component of coating material is thermally decomposed, or it reacts with other vapors in the vapor phase or at the hot substrate surface so that the reaction product is deposited as a thin film.

Plasma Chemical Vapor Deposition

This method is also known as plasma assisted CVD (PACVD). In this technique for producing the glow discharge, radio frequency energy is used. Because the activation energy is provided by the plasma and not by heat, films can be produced at lower temperatures than with standard thermally activated atmospheric CVD (APCVD) and low pressure CVD (LPCVD).

Almost all the methods just outlined are useful for preparing the thin film strain gauges and strain gauge based transducers. In some cases of transducer development, more than one thin film deposition technique needs to be adopted.

METHODS TO DETERMINE THE GAUGE FACTOR OF STRAIN GAUGES

Normally the gauge factor of the commercially available strain gauges will be specified by the supplier along with the other parameters such as gauge resistance, TCR, STC number, grid dimensions, backing material, temperature range, fatigue life, maximum strain limit, and creep property. However, if the user desires to have an assessment about the suitability of the gauge for the specific practical applications and also to determine the gauge factor and resistance-strain characteristics of in-house developed gauges (especially true in the case of thin film strain gauges), it is necessary to measure the strain values by some other known standard method. A brief description of these methods is given here.

The methods to measure the gauge factor as well as the resistance-strain characteristics of the strain gauges/strain gauge materials can be broadly divided into (1) mechanical and (2) optical techniques. The mechanical methods are essentially based on the bending of beams in different configurations. They include:

- Four-point bending beam arrangement
- Beam supported at both ends
- Cantilever beam arrangement
- Beam bent over hard metal rods

In the four-point bending beam arrangement (33), the beam is held between four rolling pins, two at the top and two at the bottom (Fig. 7). This allows the application of the equal and opposite couples to both ends of a beam. As a result, the beam is subjected to pure end moments. The strain experienced by the strain gauge bonded to the surface of the beam at its center can be calculated, which involves measuring the maximum deflection at the center of the beam. This deflection measurement is possible by the use of a dial gauge or linearly variable differential transformer (LVDT).

In the case of beam supported at both ends, it is deflected by applying a force at its center (34). The strain experienced by strain gauge that is bonded on a convex surface of the beam can be calculated by measuring the thickness, length, and deflection at the center of the beam. As already mentioned, in this case the maximum deflection of the beam at its center also can be measured using either dial gauge or LVDT.

In the cantilever technique (35), a bending moment is applied to the beam by fixing one end and loading the other

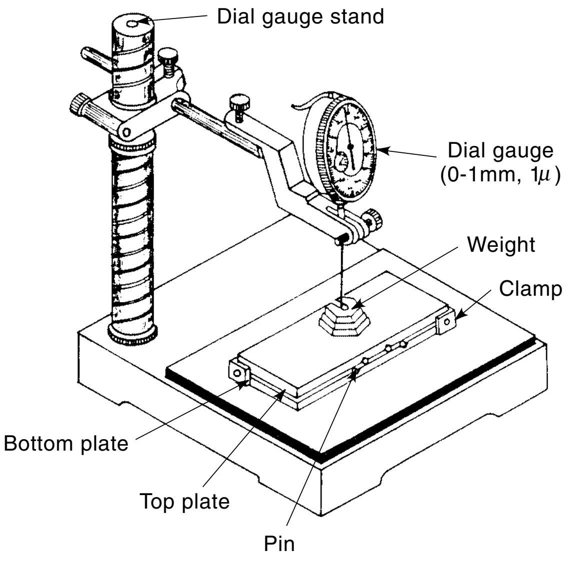


Figure 7. Schematic of the four-point bending set-up (from Ref. 33).

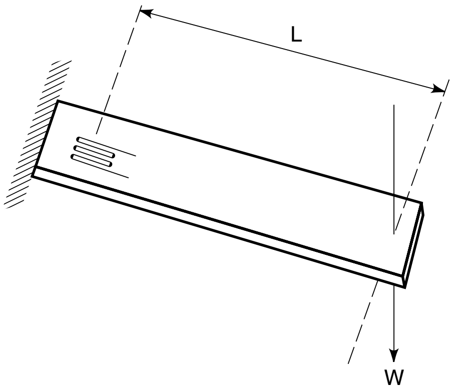


Figure 8. Cantilever set-up.

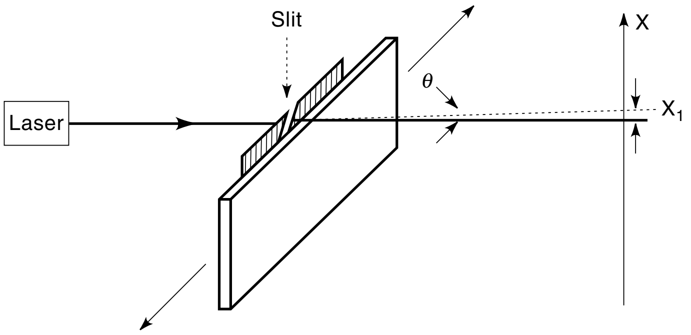


Figure 10. Schematic of the diffraction set-up to estimate the value of strain. From Sirohi, R. S. and Radhakrishna, H. C., *Mechanical Measurements,* 3/e, Copyright © M/S Wiley Eastern, Ltd. Reproduced by permission.

end with the weights (Fig. 8). Due to loading, a strain gauge cemented to the beam at a typical distance from the fixed end experiences a strain which can be calculated by knowing the dimensions of the beam, the Young's modulus of the material of the beam (E) and the weight (W) applied at the free end of the beam. It is important to note that while measuring the length of the beam, it is the length from the center of the gauge to the point of application of the load (W) which has to be taken into account for calculating the strain(ϵ).

In an arrangement (Fig. 9) in which the beam is bent over a hard metal rod (36) the strain experienced by the strain gauge (cemented at the top surface of the beam) can be calculated by measuring the thickness (t), length (L), and deflection (d) of the beam. In this case, the maximum deflection is obviously equal to the diameter of the rod on which the beam is bent. In order to subject the strain gauge to different strain values, rods of different diameters are needed.

The optical methods which are adopted to estimate the value of the strain are based on interference and diffraction phenomenon. One such method which can be employed is the diffraction method.

Diffraction Method

In this method (37), a slit with independent jaws is cemented to the test member (say a metal bar) such that its jaws are parallel as shown in Fig. 10. A laser beam is made incident on the slit. The slit diffracts the beam into various orders which are observed on the screen located at a suitable distance. Any change in the slit width due to loading will result in the corresponding change in the diffraction pattern. A tensile strain will contract the pattern, whereas a compressive strain will elongate it. Hence, the strain experienced by the strain gauge (bonded to the test member) due to loading can be calculated by making measurements on the change in the diffraction pattern produced.

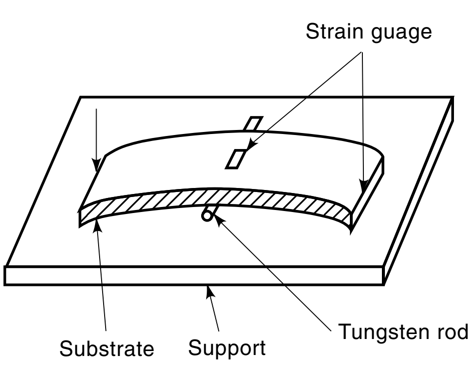


Figure 9. Schematic of the beam bent over a hard metal rod (from Ref. 36).

APPLICATION OF STRAIN GAUGES IN OTHER MEASURING SYSTEMS

Strain gauges find application as sensors in other measuring systems such as pressure transducers, load cells, displacement measuring devices, accelerometers, position sensors, stress-strain analysis systems, and so on. A brief description of some of these measuring devices is given in what follows.

PRESSURE TRANSDUCER

Pressure transducers are basically the electromechanical devices which are useful for a number of applications. Typical applications of pressure transducers include measurement of pressure in process industries, automobile engines, depth study in oceanography, wind tunnel experiments, gas turbine systems, hydraulic systems, nuclear propulsion systems, mining safety, and nuclear and aerospace applications. The primary function of the pressure transducer is to sense fluid pressure and provide an electrical output proportional to the input pressure. A pressure transducer essentially consists of an elastic element such as a metal diaphragm which undergoes deformation due to applied pressure. This mechanical deformation of the diaphragm is converted into an electrical response by a strain gauge bonded to it. Schematically, the functioning of the pressure transducer is shown in Fig. 11. There are three types of pressure transducers, namely, absolute, relative (gauge), and differential pressure transducers (Fig. 12).

Absolute Pressure Transducer. This measures pressure referenced to vacuum, hermetically sealed at about 10^{-5} m bar of Hg. When the pressure port is exposed to the atmosphere, the transducer will indicate atmospheric pressure; approximately 760 mm of Hg or 1 bar. This occurs because there is a

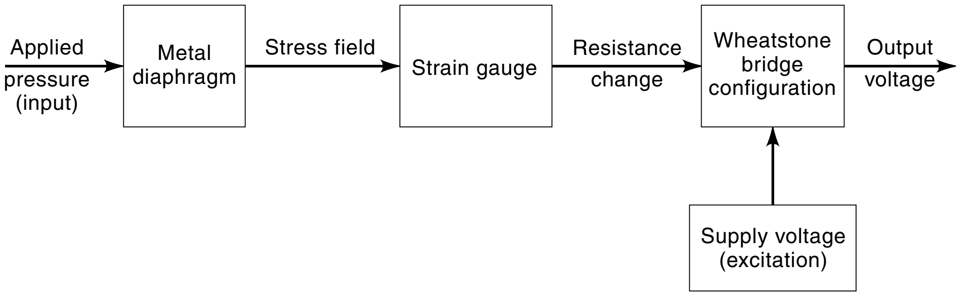


Figure 11. Block diagram of the principle of strain gauge pressure transducer.

vacuum on one side of the diaphragm and atmospheric pressure on the other.

Relative or Gauge Pressure Transducer. This measures pressure referenced to local atmospheric pressure and is vented to the atmosphere. When the pressure port is exposed to the atmosphere, the transducer will indicate 0 mm of Hg or 0 bar. This occurs because the pressure on both sides of the diaphragm is the same and there is no net output. Venting is accomplished by means of a small hole located near the transducer's electrical termination-connector/cable. The vent hole contains a porous, stainless steel disk designed to filter out harmful air-borne particles from entering the transducer in order to safeguard the strain gauges from contamination, corrosion, and hence resistance/output variation.

Differential Pressure Transducer. This measures pressure differential between two pressure P_1 and P_2 as shown in Fig. 12. When both the pressure ports (P_1 and P_2) are exposed to the atmosphere, the transducer will indicate 0 mm of Hg or 0 bar. In other words, if the pressures P_1 and P_2 are the same, the net output is 0 bar. If they are not the same, then the net output will be a reading other than 0 bar.

Application of pressure results in deformation of the sensing element (diaphragm or other type of elastic sensing elements) on to which strain gauges are bonded and wired in the Wheatstone bridge configuration. The change in the output of the bridge is related to the magnitude of the pressure. Since the resistance change of the strain gauge is a function of surface strain, this strain is directly related to the applied pressure. Hence, strain gauges form an important component of the pressure transducers.

A cross-sectional view of the complete absolute type strain gauge pressure transducer assembly is shown in Fig. 13. Either foil type strain gauges or thin film strain gauges can be utilized in these transducers. The use of thin film strain gauges for the measuring systems of this type have the additional advantage that the gauges can be directly deposited (with a dielectric film for insulation) on the diaphragm. This process enables elimination of the likely limitation of accuracy in the case of foil type gauges, because of the presence of adhesive and backing material. A schematic diagram of the thin film strain gauge pattern (38) deposited on the diaphragm is shown in Fig. 14. It is possible to obtain the required strain gauge pattern by using precision mechanical masks or photolithography technique (especially for very fine line patterns). Referring to Fig. 14, it is important to note that the location of the strain gauges is such that the gauges C_1 and C_2 at the diaphragm edge experience a compressive strain and those near the center (T_1 and T_2) undergo tensile strain. All the four gauges are made active by connecting them in Wheatstone bridge configuration. Gauges C_1 and C_2 experience compressive strain whose resistance decreases with pressure will form one opposite set of arms. The strain gauges whose resistance increases with pressure form the other set. Pressure transducers are normally calibrated using standard dead weight pressure calibration set-up.

Suitability of the pressure transducers for a specific application can be assessed from their general specifications as well as output performance characteristics such as variation

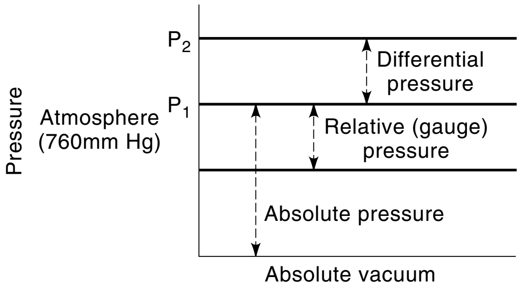


Figure 12. Types of pressure transducers.

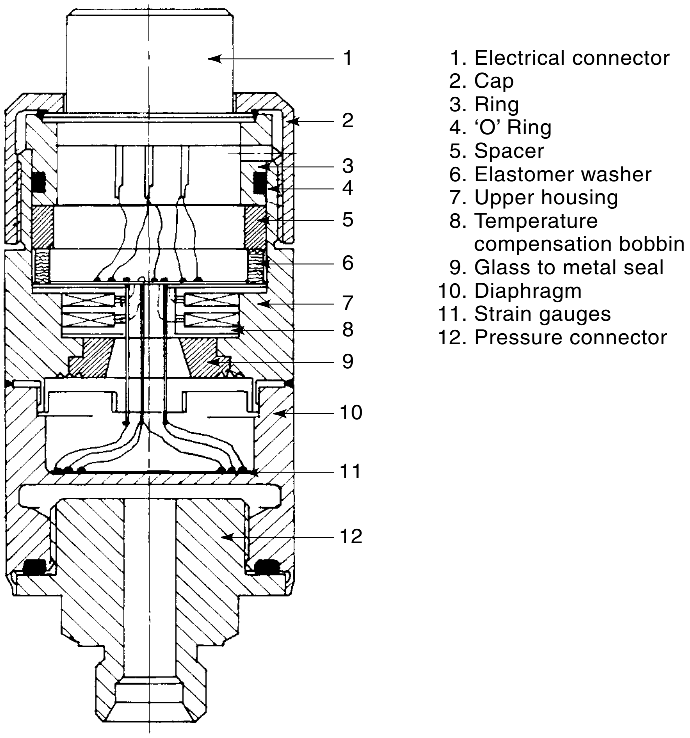


Figure 13. Cross-sectional view of pressure transducer assembly (from Ref. 33).

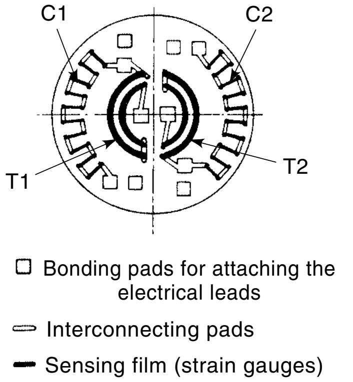


Figure 14. Schematic of the thin film strain gauge pattern deposited on the pressure transducer diagram. Reproduced from Performance study of pressure transducer with meandering—Path thin film strain gauges. M. M. Nayak, K. Rajanna, and S. Mohan, *Thin Solid Films* 193/194 (1990), p. 1023–1029. Copyright © Elsevier Science. Reprinted with permission.

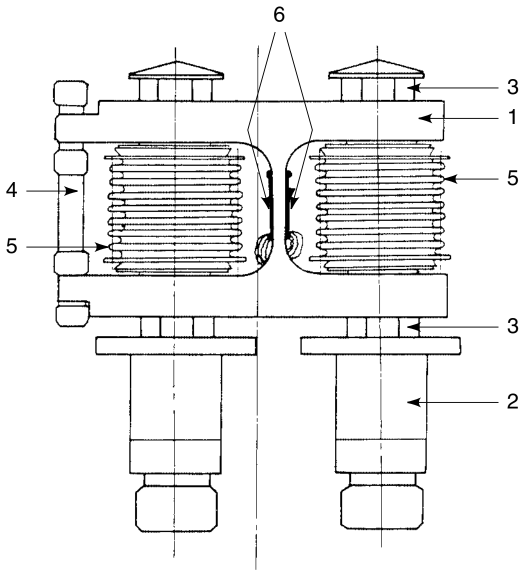
of output with pressure at different excitation voltages, nonlinearity and hysteresis, stability, repeatability, temperature effects, and so on.

Similar to absolute and gauge pressure transducers, *differential pressure transducers* are made using strain gauges. A differential pressure transducer gives an output with increasing difference between two pressures, both of which may vary. Normally, the lower or less varying pressure is termed as the reference pressure or the line pressure and the other pressure is called the measured pressure. When the measured pressure is always higher than the reference pressure, the transducer has a unidirectional range. When the measured pressure is either lower or higher than the reference pressure, the transducer is said to have bidirectional range. However, in either case, the measurement of differential pressure is of great value. Figure 15 shows the schematic of the strain gauge based on differential pressure transducer assembly (39). It essentially consists of an H beam configuration with a set of bellows as a sensing element. The two thin walled bellows used on either of the H beams convert the pressure difference into a linear displacement.

As in the case of a absolute or gauge pressure transducer, in this case a foil type or thin film strain gauges (two gauges on either side of the beam) also can be adopted for converting the linear displacement into a proportional electrical output. Figure 16 shows the schematic of the thin film strain gauges deposited on the H-beam sensing element. The Wheatstone bridge configuration with all the four gauges active is shown in Fig. 17. Calibration of the device can be done using a standard differential pressure calibration system (Fig. 18).

LOAD CELLS

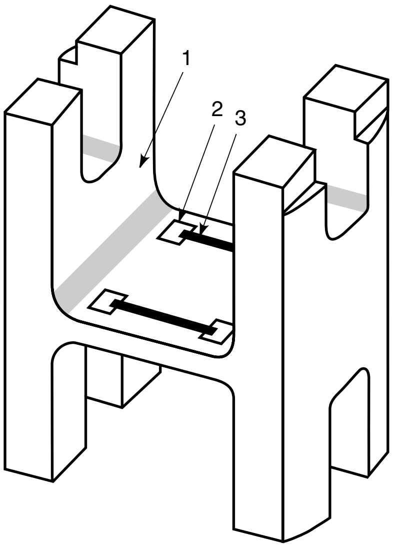
Basically the load cells are the force transducers which are used for force or thrust measurement and weighing purposes. Like pressure transducers, load cells can be made using strain gauges (3,40,41). Typical common areas of applications of strain gauge load cells include on-board weighing for trucks, postal & shipping scales, crane and laboratory weighing systems, agricultural applications, thrust measurement in static testing of rocket motors, high altitude testing systems, and others.



1. H-beam sensing element
2. Bellow support & pressure port
3. Position keys
4. Stopper
5. Bellows
6. Thin film strain gauges

Figure 15. Strain gauge based differential pressure transducer assembly. Reproduced from Sputtered thin film strain gauges for differential pressure measurement. M. M. Nayak, et al., *IEEE Trans. Instrum. and Meas.,* **45** (1) February 1996, p. 335–339. Copyright © IEEE, Inc. Reprinted with permission.

The construction of strain gauge load cells are based on three types of strain fields, namely bending, shearing, and direct stress. Accordingly, the different types of sensing ele-



1. 'H'-beam sensing element
2. Bonding contact pads
3. Sensing film (strain gauges)

Figure 16. Schematic of the thin film strain gauges on the H beam. Reproduced from Sputtered thin film strain gauges for differential pressure measurement. M. M. Nayak, et al., *IEEE Trans. Instrum. and Meas.,* **45** (1) February 1996, p. 335–339. Copyright © IEEE, Inc. Reprinted with permission.

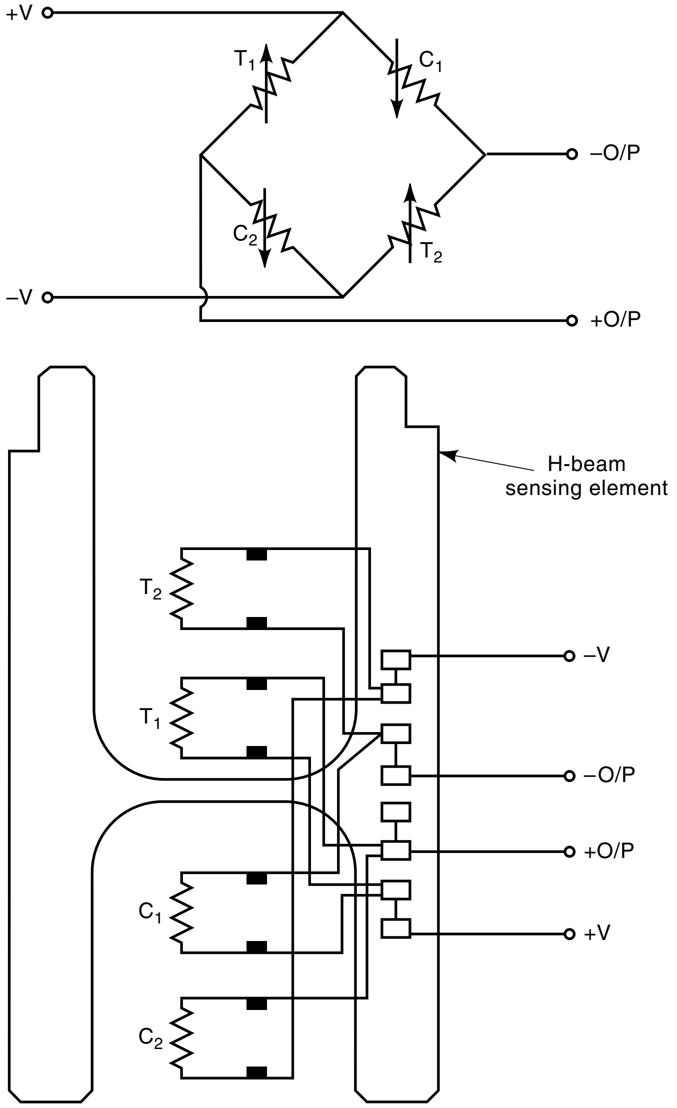


Figure 17. Four active gauges on the sensing element of the differential pressure transducer connected in the Wheatstone bridge configuration.

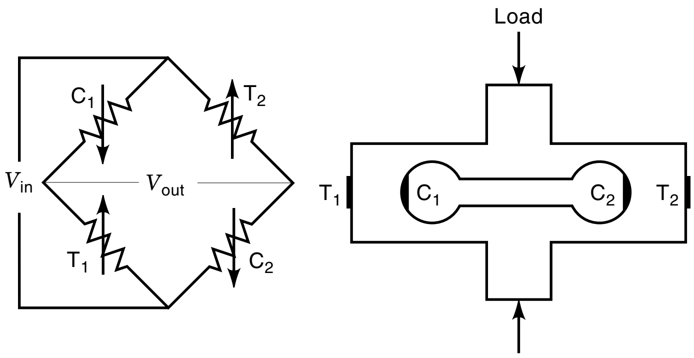


Figure 19. Binocular type sensing element configuration for load cell.

ments are adopted in load cells. Some of the commonly used sensing element configurations are hallow cylinder, slotted-cylinder, binocular type, ring type, wheel-shaped configuration, coupled dual-beam, and cantilever beam type. A typical binocular type and ring type configuration are shown in Figs. 19 and 20 respectively. Depending on the range of load, appropriate materials and configurations are chosen for the sensing element. Also overload protection will be normally provided in load cells.

As pointed out earlier, strain gauges find application in several other measuring systems. Information on these as well as related aspects including analysis of strain gauge data can be found in Refs. 3, 6, 37, 42, and 43.

SUMMARY

Strain gauges and strain gauge based sensors/transducers find a wide variety of applications in many branches of science and engineering. In this article, most of the important aspects of strain sensors are presented. However, for some of the related aspects such as surface preparation of specimens, bonding of strain gauges, soldering and wiring, providing moisture and environmental protection, output standardization, shielding and grounding, curing and post-curing, and so on each manufacturer recommends its own standard procedures. This information is available as “Technical Notes” from

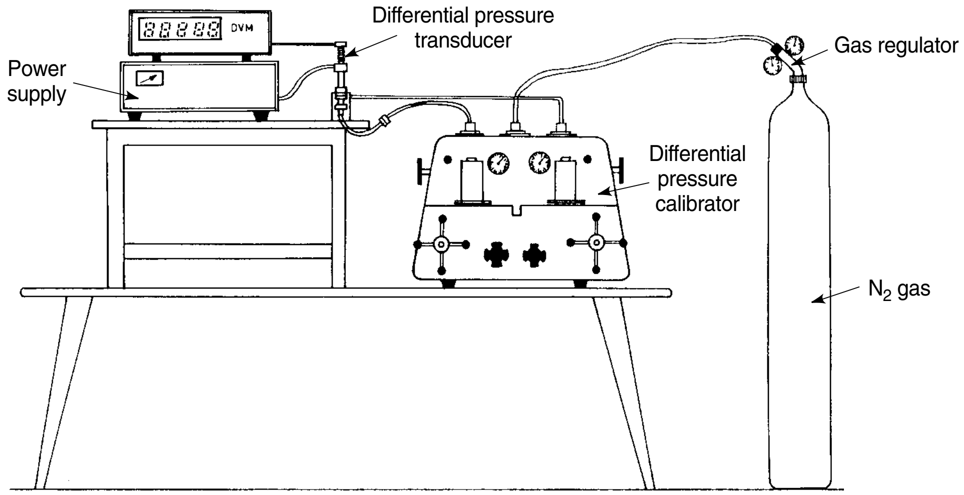


Figure 18. Schematic of the differential pressure calibration set-up. Reproduced from Sputtered thin film strain gauges for differential pressure measurement. M. M. Nayak, et al., *IEEE Trans. Instrum. and Meas.,* **45** (1) February 1996, p. 335–339. Copyright © IEEE, Inc. Reprinted with permission.

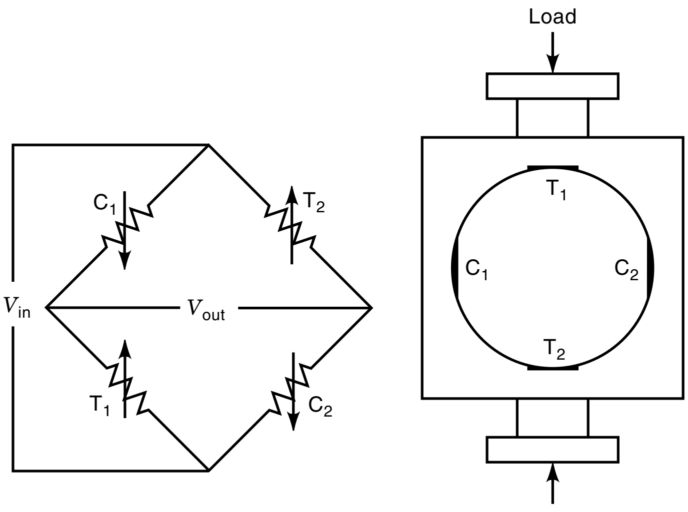


Figure 20. Ring type sensing element configuration for load cell.

the manufacturers. Some of the known strain gauge/strain gauge based transducers manufacturers are: (1) Micro Measurements, U.S.A., (2) Hottingen Baldwin Messtechnik (HBM), Germany, (3) Kulite, U.S.A., (4) Motorola, U.S.A., (5) BLH Company, U.S.A., (6) Rosemount, U.S.A., (7) Transamerica Instruments, U.S.A., (8) Kyowa Electronic Instruments, Japan, (9) Tokyo Sokki Lenkyujo Company, Japan, (10) Dynisco, U.S.A. and (11) Sensotec Inc., U.S.A.

In addition to the general applications indicated in this article, in recent years strain gauge transducers have become increasingly important in areas such as biomedical instrumentation, robotics, and space and defence applications. It is possible that the combination of advanced thin film materials technology, improved design approach for sensing elements of the transducer, and compatible signal conditioning electronics will result in the development of high performance strain gauge transducers for many more important applications.

APPENDIX 1. A CHRONOLOGY OF THE MAJOR MILESTONES IN THE HISTORY OF STRAIN GAUGE DEVELOPMENT

1856	Lord Kelvin, England Investigated the variation in electrical resistance of wires with increasing strain.
1908	S. Lindeck, Germany Development of a method of measuring high pressure (800 PSI) using fine manganin wire wrapped around a copper tube.
1923	P. W. Bridgman, Massachusetts, U.S.A. Confirmed Lord Kelvin's results in a series of tests involving wires under hydrostatic pressure.
1938–1945	A. C. Ruge, Massachusetts, U.S.A. E. E. Simmons, California, U.S.A. Considered as the co-inventors of the bonded wire strain gauge. First patent issued to E. E. Simmons on April 13, 1943. Subsequent patents issued to A. C. Ruge on strain gauges and transducers.
1950	Technograph LTD, England Foil strain gauge introduced using printed circuit technology.

Around 1958–1960 Introduction of semiconductor strain gauges.

Around 1970s Introduction of thin film strain gauges.

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STRAY LOSS. See Eddy currents.

STREAMING ELECTRIFICATION. See Static electrification.

STREET LIGHTING. See Lighting.

STRENGTH, ELECTRIC. See Electric strength.