Chapter 5

Transducers

Electrical quantities, such as current, voltage, etc. themselves produce electrical signals. Hence their measurements involve proper conditioning of the signals and displaying them in convenient ways. Transducers are seldom necessary in such measurements. Sometimes called *sensors*[1] or *detectors*, transducers more often than not constitute the first stage of an instrumentation set up for the measurement of non-electrical quantities.

A transducer is a device which receives energy in one form or state and transfers it to a convenient form or state. So, transduction is just not conversion of energy from one form to another, although sometimes it may be so. For example, a diaphragm will produce a displacement on the application of pressure. Now, pressure and displacement are both manifestations of mechanical energy, though from the measurement point of view the displacement is more convenient. So, a diaphragm is a pressure transducer although it does not convert energy from one form to another. Again, a junction of dissimilar metals—thermocouple—produces an electrical output with the change of temperature. Here, it is a case of conversion of heat energy to an electrical one, the latter being preferred from the standpoint of convenience of measurement. A thermocouple is, therefore, a temperature transducer.

The transducer, or the responding device can be mechanical, electrical, optical, acoustic, magnetic, thermal, nuclear, chemical or any of their combinations. But, of course, devices with electrical output are preferred for the following reasons:

1. The signal can be conditioned, i.e. modified, amplified, modulated, etc. as desired.
2. A remote operation as well as multiple readout is possible.
3. Devices, such as op-amps are available to ensure a minimal loading of the system.
4. Observer-independent data acquisition and minute control of the process with the help of microprocessors, or for that matter computers, are possible.

5.1 Classification of Transducers

Transducers can broadly be divided into the following categories:

1. Active and passive transducers
2. Analogue[2] and digital transducers
3. Primary and secondary transducers
4. Direct and inverse transducers

[1] Some authors prefer to reserve this word for passive transducers only.
[2] We will use the British spelling instead of the American spelling *Analog*.

Active and Passive Transducers

Active transducers are self-generating devices, their functioning being based on conversion of energy from one form to another. And since they generate energy themselves, no external source of energy is necessary to excite them. For example, the thermocouple is an active transducer. Depending on their principles of operation, active transducers can be

1. Thermoelectric
2. Piezoelectric
3. Photovoltaic
4. Electromagnetic
5. Galvanic

Table 5.1 gives a rough idea of the use of different kinds of active transducers in the measurement of representative non-electrical properties.

Table 5.1 Active transducers

Property used	*Device*	*Application in the measurement of*
Thermoelectricity generation	Thermocouple	Temperature
	Thermopile	Radiation pyrometry or temperature of distant objects
	Thermocouple gauge	Low pressure
Piezoelectricity generation	Piezoelectric transducer	Pressure
Photoelectricity generation	Photodiode in combination with a diaphragm	Pressure
Electricity generation by moving a coil in a magnetic field	Electromagnetic pick-up	Flow

Passive transducers, on the other hand, do not generate any energy. They need be excited by the application of electrical energy from outside. The extracted energy from the measurand produces a change in their electrical state which can be measured. For example, a photoresistor can be excited by an emf from a cell and the voltage against the photoresistor can be measured. When exposed to a light of certain intensity (measurand) its resistance changes, thus changing the voltage across it.

Depending on their principles of operation, passive transducers can be

1. Resistive
2. Inductive
3. Capacitive
4. Magnetoresistive
5. Photoconductive
6. Thermoresistive
7. Elastoresistive
8. Hall effect-based.

Table 5.2 gives a rough idea of the use of different kinds of passive transducers in the measurement of representative non-electrical properties.

Table 5.2 Passive transducers

Property used	*Device*	*Application in the measurement of*
Resistance variation	Potentiometer	Displacement
	Strain gauge	Small displacement useful in the measurement of strain, pressure, force, torque
	Pirani gauge	Low pressure
	Hot-wire anemometer	Flow
	Platinum resistance thermometer	Temperature
	Thermistor	Temperature
	Photoconductive cell or light-dependent-resistor (LDR) in combination with a diaphragm	Pressure
Inductance variation	Linear variable differential transformer (LVDT)	Displacement
	Synchro	Angular displacement
	Eddy-current gauge	Displacement
Capacitance variation	Capacitor gauge	Displacement, pressure
	Dielectric gauge	Liquid level, thickness (which are basically displacements)

The lists are not exhaustive but representative. As discussed earlier, we are dealing with electrical transducers only because of their adaptability to instrumentation.

Analogue and Digital Transducers

An *analogue transducer*, such as a CdS cell[3] might be wired into a circuit in a way that it will have an output that ranges from 0 volt to 5 volt. The value is continuous between 0 and 5 volt. An analogue signal is one that can assume any value in a range. It works like a tuner on an older radio. We could turn it up or down in a continuous motion. We could fine tune it by turning the knob ever so slightly. Transducers that we have discussed so far generate analogue outputs.

But *digital transducers* generate output in the discrete form. This means that there is a range of values that the sensor can output, but the values increase in steps. Discrete signals typically have a stair step appearance when they are graphed on chart. Consider a modern television set tuner. It allows us to change channels in steps. Or, consider a push button switch. This is one of the simplest forms of sensors. It has two discrete values. Either it is

[3]Cadmium Sulphide cells measure light intensity.

ON, or it is OFF. Other discrete transducers might provide us with a binary value. Digital displacement encoders[4] belong to this category.

Primary and Secondary Transducers

A transducer is said to be a *primary transducer* when the applied signal is directly sensed by it. A transducer producing output in the electrical format may be the first element in an instrumentation system. Generally, such sensing elements are called primary transducers.

Sometimes, as for example in pressure measurement, a mechanical sensor senses the input and then another device converts the output of that sensor to an electrical format. There, the latter sensors are called *secondary transducers.*

Direct and Inverse Transducer

A *direct transducer* is a device which receives energy in one form or state and transfers it to an electrical signal. The sensing device can be mechanical, optical, acoustic, magnetic, thermal, nuclear, chemical or any of their combinations.

Inverse transducer is the transducer which converts electrical quantity into a non-electrical quantity. A current carrying coil moving in a magnetic field may be called an inverse transducer because the current carried by it is converted to a force which causes translational or rotational displacement. Many data indicating and recording devices are practically inverse transducers. For example, an analogue ammeter or voltmeter converts current to the mechanical rotation of a pointer, or a speaker in a public address system converts voltage to vibration of air which produces sound.

5.2 A Few Phenomena

Now we will consider a few not so well-known phenomena based on which transducers are constructed. They are:

1. Magnetic effects
2. Piezoelectricity
3. Piezoresistivity
4. Surface acoustic wave
5. Optical effects

Magnetic Effects

All the magnetic effects that are of importance for production of transducers are given in Table 5.3.

Of these effects, magnetoelastic effects—namely, Joule effect, Villari effect, Wiedemann effect and Matteucci effect—and Hall effect are finding more and more use in so-called smart sensors. So we discuss these effects in a little more detail here.

[4]See Section 6.6 at page 216.

Table 5.3 Magnetic effects used in transducers

Effect	*Year of discovery*	*What it is*	*Application*
Faraday effect	1831	Generation of electricity in a coil with the change in the ambient magnetic field	Reluctance based transducers
Joule effect (Magnetostriction)	1842	Change in shape of a ferro-magnetic body with magnetisation	In combination with piezo-electric elements for magneto-meters and potentiometers
ΔE effect	1846	Change in Young's modulus with magnetisation	Acoustic delay line components for magnetic field measurement
Matteucci effect	1847	Torsion of a ferromagnetic rod in a longitudinal field changes magnetisation	Magnetoelastic sensors
Thomson effect	1856	Change in resistance with magnetic field	Magnetoresistive sensors
Wiedemann effect	1858	A torsion is produced in a current carrying ferromagnetic rod when subjected to a longitudinal field	Torque and force measurement Displacement measurement Level measurement
Villari effect	1865	Effect on magnetisation by tensile or compressive stress	Magnetoelastic sensors
Hall effect	1879	A current carrying crystal produces a transverse voltage when subjected to a magnetic field vertical to its surface	Magnetogalvanic sensors
Skin effect	1903	Displacement of current from the interior of material to surface layer due to eddy currents	Distance and proximity sensors
Josephson effect	1962	Quantum tunnelling between two superconducting materials with an extremely thin separating layer	SQUID magnetometers

Magnetoelastic effects

Various aspects of the coupling between the magnetisation of the ferromagnetic materials and their elasticity can be employed to sense parameters of interest. Several effects which have application for sensing are

Direct effect	*Inverse effect*
Joule effect	Villari effect
Wiedemann effect	Matteucci effect

We discuss these effects briefly here.

Table 5.6 Applications of magnetoresistive effect

Principle	*Application*
Direct measurement of magnetic fields	Magnetic audio recording Reading machines for credit cards, magnetically coded price tags
Measuring magnetic field variation[a]	Measurement of linear and angular displacement Proximity switches Position measurement Angular velocity of ferrous gear wheels

[a] To accomplish this, it must be either a metallic object or an object with a metallic coating or an identifier placed in a constant magnetic field, or the moving element to be detected must incorporate a permanent magnet.

Piezoelectricity

Certain materials, especially the crystalline ones, produce an emf when deformed by an application of pressure along the specific axes. The phenomenon is known as *piezoelectricity*[16] or *piezoelectric effect* and is widely used for the construction of many transducers that involve the measurement of dynamic pressure.

Origin of piezoelectricity

In most crystals, the unit cell (the basic repeating unit) is symmetrical; in piezoelectric crystals, it is not. Normally, piezoelectric crystals are electrically neutral—the atoms inside them may not be symmetrically arranged, but their electrical charges, are perfectly balanced. A quartz (SiO_2) tetrahedron is shown in Fig. 5.9. When a pressure is applied to the tetrahedron (or a macroscopic crystal element) a displacement of the positive ion charge towards the centre of the negative ion charges occurs. Hence, the outer faces of such a piezoelectric element get charged under this pressure.

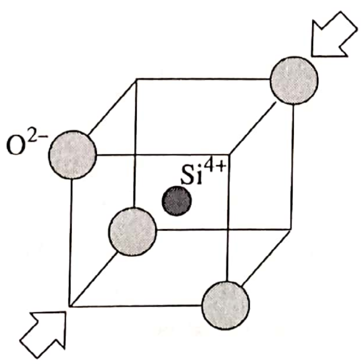

Fig. 5.9 Piezoelectricity generation in quartz. Arrows indicate the direction of application of pressure.

[16] Pronounced as piē'zō or pēā'zō (Webster's Universal Collegiate Dictionary, 1997). The prefix is a Greek word meaning *squeeze*.

Conversely, when an electric field is applied to a piezoelectric crystal, a mechanical strain is produced in it. This is sometimes called the *inverse piezoelectric effect.* If an alternating field is applied to such a crystal, the strain also varies periodically—but generally there is a phase lag between the applied field and the resulting strain, depending on the frequency of the applied field. At the natural frequency of vibration of the crystal, called the *resonance frequency,* the two are exactly in phase. This effect is utilised to construct resonant transducers and also to stabilise frequency in electronic clocks.

Piezoelectric materials

Generally, piezoelectric materials are classified into the following four categories:

Category	*Examples*
Naturally occurring single crystals	Quartz Tourmaline Topaz Cane Sugar Rochelle salt (potassium sodium tartrate tetrahydrate, $KNaC_4H_4O_6$, $4H_2O$)
Man-made crystals	Gallium Orthophosphate ($GaPO_4$) Langasite ($La_3Ga_5SiO_{14}$)— both quartz analogous crystals
Man-made polycrystalline ceramic materials	Barium Titanate ($BaTiO_3$) Lead Zirconate Titanate ($Pb[Zr_xTi_{1-x}]O_3$ where $0 < x < 1$)—more commonly known as PZT Lead Titanate ($PbTiO_3$) Potassium Niobate ($KNbO_3$) Lithium Niobate ($LiNbO_3$) Lithium Tantalate ($LiTaO_3$) Sodium Tungstate ($NaWO_3$)
Man-made polymers	PolyVinyliDene Fluoride (PVDF)

PZT is the most common piezoelectric ceramic in use today. Among the naturally occurring crystals, quartz is inexpensive. Tourmaline, a naturally occurring semi-precious form of quartz, has sub-microsecond response time and, therefore, very useful in the measurement of rapid transients.

PVDF exhibits piezoelectricity several times greater than quartz. Unlike ceramics, where the crystal structure of the material creates the piezoelectric effect, in polymers the intertwined long-chain molecules attract and repel each other when an electric field is applied.

The so-called natural crystals are already polarised and the piezoelectric element is usually a cut from the crystal in the direction of any of the electrical axes (called X-axes) or mechanical axes (called Y-axes)[Fig. 5.10(a)]. Figures 5.10(b) and (c) show how an X-cut piece of the hexagonal quartz crystal can be obtained.

Synthetic polycrystalline ceramic materials have to be baked under a strong dc electric field to provide polarisation. Thus, they have the advantage of being moulded into any shape or size.

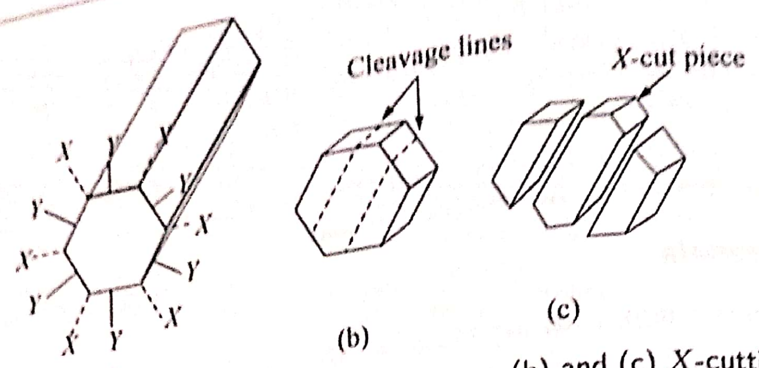

Fig. 5.10 Quartz crystal: (a) X and Y axes, (b) and (c) X-cutting

Curie temperature. The Curie temperature T_C is the temperature at which the piezoelectric material changes to a non-piezoelectric form. Before polarisation or above Curie temperature[17], PZT crystallites have symmetric cubic unit cells [Fig. 5.11(a)]. Below the Curie temperature, the lattice structure becomes deformed and asymmetric. The unit cells then exhibit spontaneous polarisation [Fig. 5.11(b)], i.e. the individual PZT crystallites become piezoelectric.

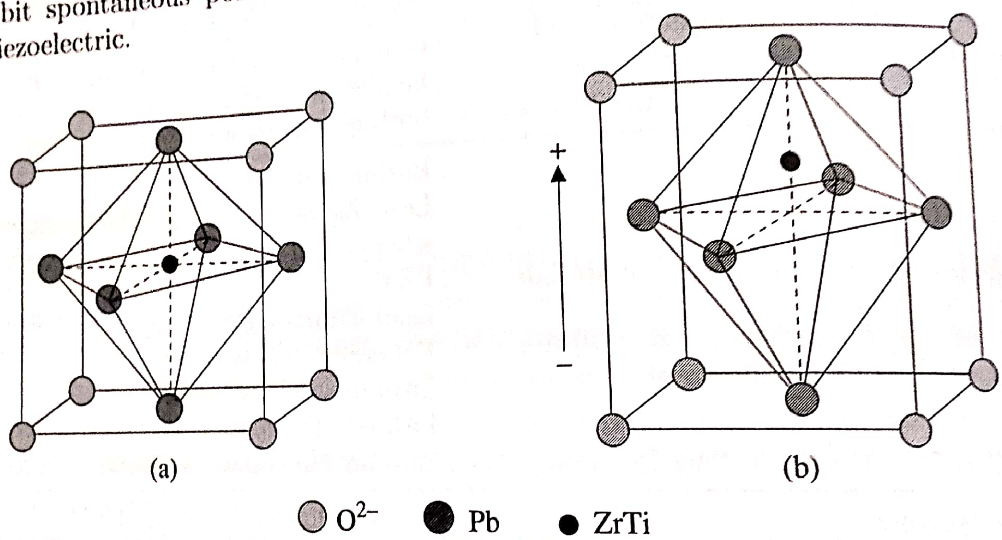

Fig. 5.11 PZT unit cell: (a) Perovskite-type PZT unit cell in the symmetric cubic state above the Curie temperature, and (b) tetragonally distorted unit cell below the Curie temperature.

Domains. Groups of unit cells with the same orientation of polarisation are akin to Weiss *domains* of ferromagnetism. The random distribution of the domain orientations in the ceramic material manifests no macroscopic piezoelectric behaviour [Fig. 5.12(a)]. Due to the ferroelectric[18] nature of the material, it is possible to force permanent alignment of the different domains using a strong electric field. This process is called *poling* [Fig. 5.12(b)]. Some PZT ceramics must be poled at an elevated temperature to acquire a remnant

[17]Named after brothers Pierre and Jacques Curie of France who discovered piezoelectricity in 1880.

[18]Dielectrics which show hysteresis effect for applied field and polarisation are called *ferroelectrics*. A ferroelectric is spontaneously polarised, i.e. it is polarised in the absence of an electric field. Since the dielectric behaviour of these materials is in many respects analogous to the magnetic behaviour of ferromagnetic materials, they are called *ferroelectric solids*.

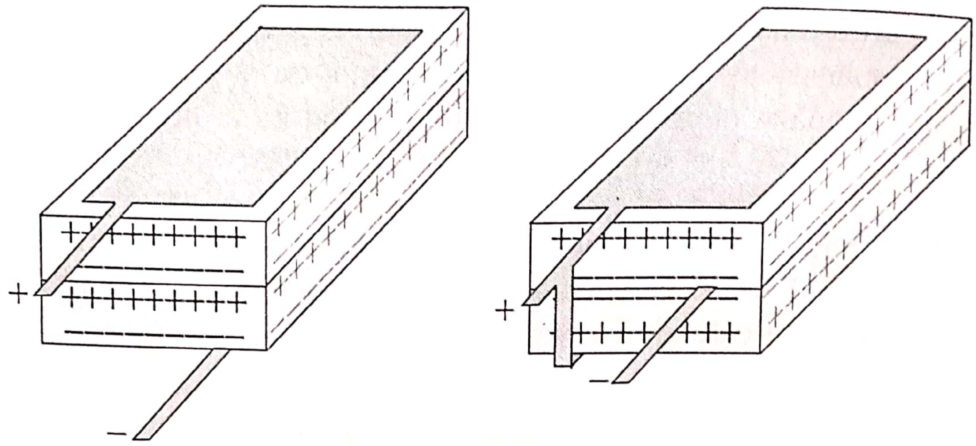

Fig. 5.22 Bimorphs: (a) serial and (b) parallel.

Parallel bimorph produces twice the capacitance as that of a series connection and in a sender-type transducer admits the full excitation voltage across each plate.

In either case the device relies on the d_{31} piezoelectric constant and that the strain is proportional to the square of the applied voltage.

Multimorph. Instead of two plates, monolithic, multi-layer type piezo benders, known as *multimorphs*, are available too. Similar to multilayer stack actuators, they run on a low operating voltage (60 to 100 V).

Bender type actuators provide large motion in a small package at the expense of stiffness, force and speed.

Advantages and disadvantages

From its discovery by the Curies in 1880, it took about 70 years before the piezoelectric effect was used for industrial sensing applications. Since then, its utilisation has experienced a constant growth and can nowadays be regarded as a mature technology with an outstanding inherent reliability. It has been successfully used in various critical applications like in medical, aerospace and nuclear instrumentation.

Advantages. The high modulus of elasticity of many piezoelectric materials is comparable to that of many metals and the maximum stress that they can withstand can be as high as 105×10^6 N/m^2. Even though piezoelectric sensors are electromechanical systems that react on compression, the sensing elements show almost zero deformation. The piezoelectric sensors are

1. Rugged
2. Have an extremely high natural frequency
3. An excellent linearity over a wide amplitude range
4. Insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions
5. Materials like gallium phosphate or tourmaline have an extreme stability over temperature enabling sensors to have a working range of 1000°C

Table 5.10 gives an idea about the relative standing of piezoelectric transducers vis-á-vis the strain sensitivity of other transducers.

We would like to mention in this context that many creatures make an interesting use of piezoelectricity. Bones are piezolelectric materials and they act as force sensors. Once loaded, bones produce charges proportional to the resulting internal strain. Those charges stimulate and drive the development of new bone material. This leads to the strengthening of structures where the internal displacements are the greatest. Thus, with time weaker structures increase their strength and stability as material is laid down proportional to the forces affecting the bone.

Piezoresistivity

The piezoresistive effect is the change of electric resistivity of the material caused by an applied mechanical stress. Many materials change their resistance when stressed, but the piezoresistive effect is the most pronounced in semiconductors. Semiconductor piezoresistive sensing elements, or piezoresistors, are typically used as pressure and force sensors, where the applied mechanical load is converted into a proportional electric signal.

Origin of piezoresistivity

It is apparent that piezoresistivity has nothing to do with piezoelectricity, though some piezoresistors are piezoelectric as well for reasons different altogether.

When a semiconducting material is stressed, the interatomic spacings within the material change. This eventually changes the bandgaps in each atom making it easier (or harder depending on the material and strain) for electrons to be raised into the conduction band. A higher or lower electron population in the conduction band results in a change in resistivity of the semiconductor.

We know that the resistance R of a conductor is given by

$$R = \rho \frac{l}{A}$$

where ρ is the resistivity of the material of the conductor
l is the length of the conductor
A is the area of cross-section of the conductor.

For metals, ρ is more or less a constant at a given temperature because their conduction bands are already sufficiently populated with electrons. But the conduction bands of semiconductors are not so populated normally and as already discussed, at a given temperature ρ varies for semiconductors when they are stressed. For them the piezoresistivity ρ_σ is defined by

$$\rho_\sigma = \frac{d\rho/\rho}{\varepsilon}$$

where $d\rho$ is the change in resistivity
ρ is the original resistivity
ε is the strain

Now, when a semiconductor is strained, its length and area of cross-section will eventually change with a consequent change in its resistance. But its piezoresistive change can be several orders of magnitudes larger than the geometrical effect. This effect is conspicuous in materials like germanium, polycrystalline silicon, amorphous silicon, silicon carbide, and single crystal silicon.

Piezoresistors

Piezoresistors are fabricated using a wide variety of piezoresistive materials. The simplest form of silicon piezoresistors are diffused resistors. They consist of a simple two contact diffused n or p-well within a p or n-substrate. The typical square resistances of these devices are in the range of several hundred ohms. This necessitates additional p^+ or n^+ diffusions to facilitate ohmic contacts to the device (Fig. 5.23).

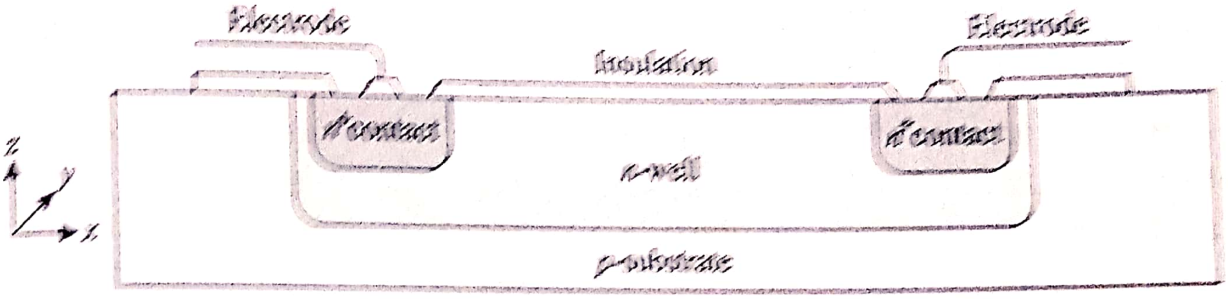

Fig. 5.23 Schematic cross-section of an elementary silicon n-well piezoresistor.

For typical stress values in the order of mPa, the piezoresistivity can be written as

$$\rho_\sigma = \frac{d\rho/\rho}{\varepsilon} = \pi Y$$

where π is the piezoresistive coefficient and Y is the Young's modulus. Both π and Y depend on

1. Basic material, now mostly silicon
2. Majority carriers, i.e. p or n
3. Crystal orientation given by Miller indices like (100) or (111)
4. Angle between the current and stress; the stress may be tensile, shear or volume compression
5. Degree of doping indicated by the room-temperature resistivity ρ_0
6. Size and shape of the resistor

In general, both the stress and the current are along the length of the piezoresistor. Then, the relation for the longitudinal piezoresistance coefficient is given by

$$\pi_1 = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})(\alpha_1^2\beta_1^2 + \alpha_1^2\gamma_1^2 + \beta_1^2\gamma_1^2)$$

where π_{11}, π_{12}, π_{44} are the fundamental piezoresistive coefficients, the subscripts referring to the current and stress directions

α_1, β_1, γ_1 are the direction cosines of the current with respect to the crystallographic axes