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General
Appendices

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THE MAGNETORESISTIVE EFFECT

Magnetoresistive sensors make use of the fact that the electrical resistance ρ of certain ferromagnetic alloys is influenced by external fields. This solid-state magnetoresistive effect, or anisotropic magnetoresistance, can be easily realized using thin film technology, so lends itself to sensor applications.

Resistance- field relation

The specific resistance ρ of anisotropic ferromagnetic metals depends on the angle Θ between the internal magnetization M and the current I, according to:

$$\rho(\Theta) = \rho_{\perp} + (\rho_{\perp} - \rho_{||}) \cos^2 \Theta \qquad (1)$$

where $\rho_{\perp}$ and $\rho_{||}$ are the resistivities perpendicular and parallel to M. The quotient $(\rho_{\perp} - \rho_{||})/\rho_{\perp} = \Delta\rho/\rho$ is called the magnetoresistive effect and may amount to several percent.

Sensors are always made from ferromagnetic thin films as this has two major advantages over bulk material: the resistance is high and the anisotropy can be made uniaxial. The ferromagnetic layer behaves like a single domain and has one distinguished direction of magnetization in its plane called the easy axis (e.a.), which is the direction of magnetization without external field influence.

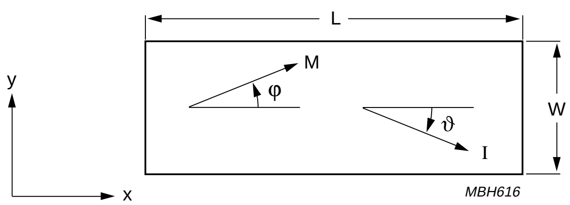

Fig.1 Geometry of a simple sensor.

Figure 1 shows the geometry of a simple sensor where the thickness (t) is much smaller than the width (w) which is in turn, less than the length (l) (i.e. t « w ‹ l). With the current (I) flowing in the x-direction (i.e. θ = 0 or Θ = ϕ) then the following equation can be obtained from equation 1:

$$R = R_0 + \Delta R \cos^2\phi \qquad (2)$$

and with a constant current I, the voltage drop in the x-direction U_x becomes:

$$U_x = \rho_{\perp} I \left(\frac{L}{wt}\right)\left(1 + \left(\frac{\Delta\rho}{\rho}\right)\cos^2\phi\right) \qquad (3)$$

Besides this voltage, which is directly allied to the resistance variation, there is a voltage in the y-direction, U_y, given by:

$$U_y = \rho_{\perp} I \left(\frac{1}{t}\right)\left(\frac{\Delta\rho}{\rho}\right)\sin\phi\cos\phi \qquad (4)$$

This is called the planar or pseudo Hall effect; it resembles the normal or transverse Hall effect but has a physically different origin.

All sensor signals are determined by the angle ϕ between the magnetization M and the ‘length’ axis and, as M rotates under the influence of external fields, these external fields thus directly determine sensor signals. We can assume that the sensor is manufactured such that the e.a. is in the x-direction so that without the influence of external fields, M only has an x-component (ϕ = 0˚ or 180˚).

Two energies have to be introduced when M is rotated by external magnetic fields: the anisotropy energy and the demagnetizing energy. The anisotropy energy E_k, is given by the crystal anisotropy field H_k, which depends on the material and processes used in manufacture. The demagnetizing energy E_d or form anisotropy depends on the geometry and this is generally a rather complex relationship, apart from ellipsoids where a uniform demagnetizing field H_d may be introduced. In this case, for the sensor set-up in Fig.1.

$$H_d \approx \frac{t}{w}\left(\frac{M_s}{\mu_0}\right) \qquad (5)$$

where the demagnetizing factor N – t/w, the saturation magnetization $M_s \approx 1$ T and the induction constant $\mu0 = 4\pi^{-7}$ Vs/Am.

The field $H_0 - H_k + t/w(M_0/m_0)$ determines the measuring range of a magnetoresistive sensor, as f is given by:

$$\sin\phi = \frac{H_y}{H_o + \frac{H_x}{\cos\phi}} \qquad (6)$$

where $|H_y| \le |H_0 + H_x|$ and H_x and H_y are the components of the external field. In the simplest case $H_x = 0$, the voltages U_x and U_y become:

$$U_x = \rho_\perp I\left(\frac{L}{wt}\right)\left(1 + \left(\frac{\Delta\rho}{\rho}\right)\left(1 - \left(\frac{H_y}{H_0}\right)^2\right)\right) \qquad (7)$$

$$U_y = \rho_\perp I\left(\frac{1}{t}\right)\left(\frac{\Delta\rho}{\rho}\right)\left(\frac{H_y}{H_0}\right)\sqrt{1 - (H_y/H_0)^2} \qquad (8)$$

(Note: if $H_x = 0$, then H_0 must be replaced by $H_0 + H_x/\cos\phi$).

Neglecting the constant part in U_x, there are two main differences between U_x and U_y:

1. The magnetoresistive signal U_x depends on the square of H_y/H_0, whereas the Hall voltage U_y is linear for $H_y \ll H_0$.
2. The ratio of their maximum values is L/w; the Hall voltage is much smaller as in most cases L » w.

Magnetization of the thin layer

The magnetic field is in reality slightly more complicated than given in equation (6). There are two solutions for angle ϕ:
$\phi1 < 90^\circ$ and $\phi2 > 90^\circ$ (with $\phi1 + \phi2 = 180^\circ$ for $H_x = 0$).

Replacing ϕ by $180^\circ - \phi$ has no influence on U_x except to change the sign of the Hall voltage and also that of most linearized magnetoresistive sensors.
Therefore, to avoid ambiguity either a short pulse of a proper field in the x-axis ($|H_x| > H_k$) with the correct sign must be applied, which will switch the magnetization into the desired state, or a stabilizing field Hst in the x-direction can be used. With the exception of $H_y \ll H_0$, it is advisable to use a stabilizing field as in this case, H_x values are not affected by the non-ideal behaviour of the layer or restricted by the so-called ‘blocking curve’.

The minimum value of H_{st} depends on the structure of the sensitive layer and has to be of the order of H_k, as an insufficient value will produce an open characteristic (hysteresis) of the sensor. An easy axis in the y-direction leads to a sensor of higher sensitivity, as then
$H_o = H_k - H_d$.

Linearization

As shown, the basic magnetoresistor has a square resistance-field (R-H) dependence, so a simple magnetoresistive element cannot be used directly for linear field measurements. A magnetic biasing field can be used to solve this problem, but a better solution is linearization using barber-poles (described later). Nevertheless plain elements are useful for applications using strong magnetic fields which saturate the sensor, where the actual value of the field is not being measured, such as for angle measurement. In this case, the direction of the magnetization is parallel to the field and the sensor signal can be described by a $\cos^2\alpha$ function.

Sensors with inclined elements

Sensors can also be linearized by rotating the current path, by using resistive elements inclined at an angle θ, as shown in Fig.2. An actual device uses four inclined resistive elements, two pairs each with opposite inclinations, in a bridge.

The magnetic behaviour of such is pattern is more complicated as M_o is determined by the angle of inclination θ, anisotropy, demagnetization and bias field (if present). Linearity is at its maximum for $\phi + \theta \approx 45^\circ$, which can be achieved through proper selection of θ.
A stabilization field (H_{st}) in the x-direction may be necessary for some applications, as this arrangement only works properly in one magnetization state.

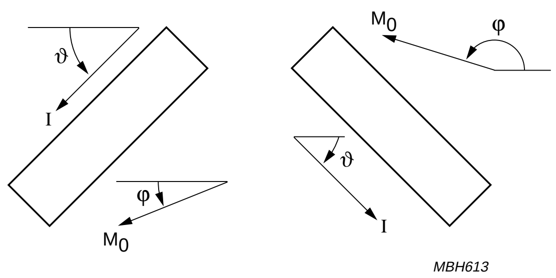

Fig.2 Current rotation by inclined elements (current and magnetization shown in quiescent state).

BARBER-POLE SENSORS

A number of Philips' magnetoresistive sensors use a 'barber-pole' construction to linearize the R-H relationship, incorporating slanted strips of a good conductor to rotate the current. This type of sensor has the widest range of linearity, smaller resistance and the least associated distortion than any other form of linearization, and is well suited to medium and high fields.

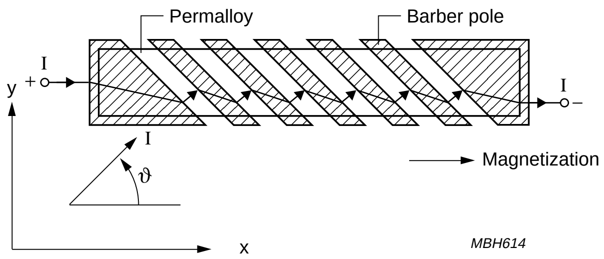

Fig.3 Linearization of the magnetoresistive effect with barber-poles (current and magnetization shown in quiescent state).

The current takes the shortest route in the high-resistivity gaps which, as shown in Fig.3, is perpendicular to the barber-poles. Barber-poles inclined in the opposite direction will result in the opposite sign for the R-H characteristic, making it extremely simple to realize a Wheatstone bridge set-up.

The signal voltage of a Barber-pole sensor may be calculated from the basic equation (1) with $\Theta = \phi + 45^{\circ}$ ($\theta = +45^{\circ}$):

$$U_{BP} = \rho_{\perp} I\left(\frac{L}{wt}\right)\alpha\left(1 + \frac{1}{2}\left(\frac{\Delta\rho}{\rho}\right) \pm \frac{\Delta\rho}{\rho}\frac{H_y}{H_0}\sqrt{1 - \left(\frac{H_y}{H_0}\right)^2}\right) \qquad (9)$$

where a is a constant arising from the partial shorting of the resistor, amounting to 0.25 if barber-poles and gaps have equal widths. The characteristic is plotted in Fig.4 and it can be seen that for small values of H_y relative to H_0, the R-H dependence is linear. In fact this equation gives the same linear R-H dependence as the planar Hall-effect sensor, but it has the magnitude of the magnetoresistive sensor.

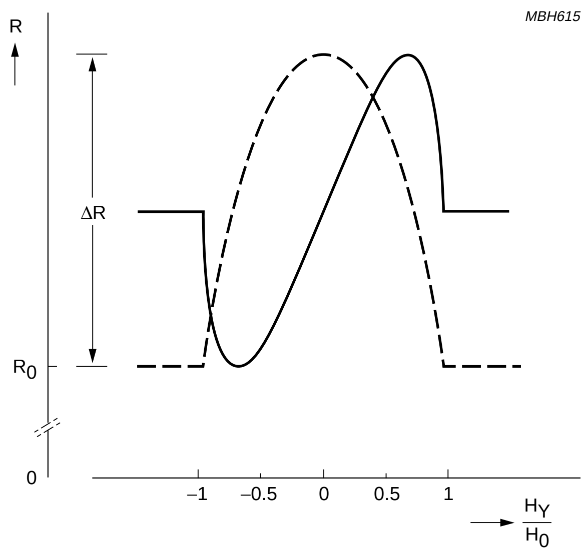

Fig.4 Calculated R-H characteristic of a barber-pole sensor.

Barber-pole sensors require a certain magnetization state. A bias field of several hundred A/m can be generated by the sensing current alone, but this is not sufficient for sensor stabilization, so can be neglected. In most applications, an external field is applied for this purpose.

Sensitivity

Due to the high demagnetization, in most applications field components in the z-direction (perpendicular to the layer plane) can be ignored. Nearly all sensors are most sensitive to fields in the y-direction, with H_x only having a limited or even negligible influence.

Definition of the sensitivity S contains the signal and field variations (DU and DH), as well as the operating voltage U_0 (as D_U is proportional to U_0):

$$S_o = \frac{\Delta U}{\Delta H}\left(\frac{1}{U_0}\right) = \left(\frac{\Delta U}{U_0 \Delta H}\right) \qquad (10)$$

This definition relates DU to a unit operating voltage.

The highest (H_G) and lowest (H_{min}) fields detectable by the sensor are also of significance. The measuring range H_G is restricted by non-linearity - if this is assumed at 5%, an approximate value for barber-pole sensors is given by:

$$H_G \approx 0.5\,(H_0 + H_x) \qquad (11)$$

From this and equation (9) for signal voltage (U_{BP}) for a barber-pole sensor, the following simple relationship can be obtained:

$$H_G S_0 \approx 0.5\left(\frac{\Delta\rho}{\rho}\right) \qquad (12)$$

Other sensor types have a narrower range of linearity and therefore a smaller useful signal.

The lowest detectable field H_{min} is limited by offset, drift and noise. The offset is nearly cancelled in a bridge circuit and the remaining imbalance is minimized by symmetrical design and offset trimming, with thermal noise negligible in most applications (see section on sensor layout). Proper film deposition and, if necessary, the introduction of a stabilization field will eliminate magnetization switching due to domain splitting and the introduction of ‘Barkhausen noise’.

Sensitivity S_0 is essentially determined by the sum of the anisotropy (H_k), demagnetization (H_d) and bias (H_x) fields. The highest sensitivity is achievable with $H_x = 0$ and $H_d \ll H_k$, although in this case S_0 depends purely on H_k which is less stable than H_d. For a permalloy with a thickness greater than or equal to 20 µm, a width in excess of 60 µm is required which, although possible, has the drawback of producing a very low resistance per unit area.

The maximum theoretical S_0 with this permalloy (at H_k = 250 A/m and $\Delta\rho/\rho$ = 2.5%) is approximately:

$$S_0(\max) = 10^{-4}\left(\frac{A}{m}\right)^1 = 100\frac{\left(\frac{mV}{V}\right)}{\left(\frac{kA}{m}\right)} \qquad (13)$$

For the same reasons, sensors with reduced sensitivity should be realized with increased H_d, which can be estimated at a maximum for a barber-pole sensor at 40 kA/m. A further reduction in sensitivity and a corresponding growth in the linearity range is attained using a biasing field. A magnetic shunt parallel to the magnetoresistor or only having a small field component in the sensitive direction can also be employed with very high field strengths.

A high signal voltage U_x can only be produced with a sensor that can tolerate a high supply voltage U_o. This requires a high sensor resistance R with a large area A, since there are limits for power dissipation and current density. The current density in permalloy may be very high ($j > 10^6$ A/cm^2 in passivation layers), but there are weak points at the current reversal in the meander (see section on sensor layout) and in the barber-pole material, with five-fold increased current density.

A high resistance sensor with U_0 = 25 V and a maximum S_0 results in a value of 2.5 x 10^{-3} (A/m)$^{-1}$ for Su or, converted to flux density, S_T = 2000 V/T. This value is several orders of magnitude higher than for a normal Hall effect sensor, but is valid only for a much narrower measuring range.

Materials

There are five major criteria for a magnetoresistive material:

- Large magnetoresistive effect Dr/r (resulting in a high signal to operating voltage ratio)
- Large specific resistance r (to achieve high resistance value over a small area)
- Low anisotropy
- Zero magnetostriction (to avoid influence of mechanical stress)
- Long-term stability.

Appropriate materials are binary and ternary alloys of Ni, Fe and Co, of which NiFe (81/19) is probably the most common.

Table 1 gives a comparison between some of the more common materials, although the majority of the figures are only approximations as the exact values depend on a number of variables such as thickness, deposition and post-processing.

Table 1 Comparison of magnetoresistive sensor materials

Materials	**ρ (10^{-8}Ωm)**	**Δρ/ρ(%)**	**II_k(Δ/m)**
NiFe 81:19	22	2.2	250
NiFe 86:14	15	3	200
NiCo 50:50	24	2.2	2500
NiCo 70:30	26	3.7	2500
CoFeB 72:8:20	86	0.07	2000

Δρ is nearly independent of these factors, but r itself increases with thickness ($t \leq 40$ nm) and will decrease during annealing. Permalloys have a low H_k and zero magnetostriction; the addition of C_o will increase $\Delta\rho/\rho$, but this also considerably enlarges H_k. If a small temperature coefficient of $\Delta\rho$ is required, NiCo alloys are preferable. The amorphous alloy CoFeB has a low $\Delta\rho/\rho$, high H_k and slightly worse thermal stability but due to the absence of grain boundaries within the amorphous structure, exhibits excellent magnetic behaviour.

APPENDIX 2: SENSOR FLIPPING

During deposition of the permalloy strip, a strong external magnetic field is applied parallel to the strip axis. This accentuates the inherent magnetic anisotropy of the strip and gives them a preferred magnetization direction, so that even in the absence of an external magnetic field, the magnetization will always tend to align with the strips.

Providing a high level of premagnetization within the crystal structure of the permalloy allows for two stable premagnetization directions. When the sensor is placed in a controlled external magnetic field opposing the internal aligning field, the polarity of the premagnetization of the strips can be switched or ‘flipped’ between positive and negative magnetization directions, resulting in two stable output characteristics.

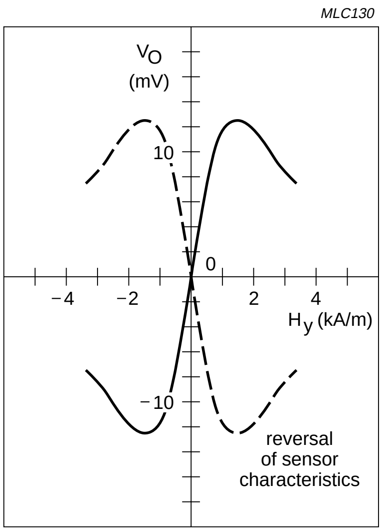

Fig.5 Sensor characteristics.

The field required to flip the sensor magnetization (and hence the output characteristic) depends on the magnitude of the transverse field H_y. The greater this field, the more the magnetization rotates towards 90˚ and therefore it becomes easier to flip the sensor into the corresponding stable position in the ‘-x’ direction. This means that a smaller -H_x field is sufficient to cause the flipping action

As can be seen in Fig.6, for low transverse field strengths (0.5 kA/m) the sensor characteristic is stable for all positive values of H_x, and a reverse field of approximately 1 kA/m is required to flip the sensor. However at higher values of H_y (2 kA/m), the sensor will also flip for smaller values of H_x (at 0.5 kA/m). Also illustrated in this figure is a noticeable hysteresis effect; it also shows that as the permalloy strips do not flip at the same rate, the flipping action is not instantaneous.

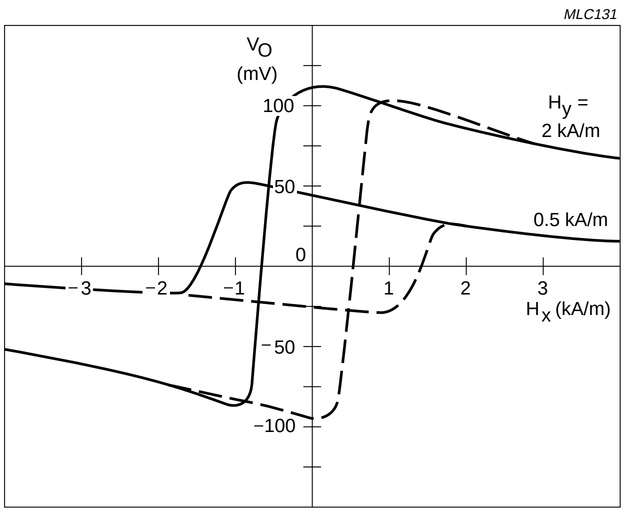

Fig.6 Sensor output ‘V_o’ as a function of the auxiliary field H_x.

The sensitivity of the sensor reduces as the auxiliary field H_x increases, which can be seen in Fig.6 and more clearly in Fig.7. This is because the moment imposed on the magnetization by H_x directly opposes that of H_y, resulting in a reduction in the degree of bridge imbalance and hence the output signal for a given value of H_y.

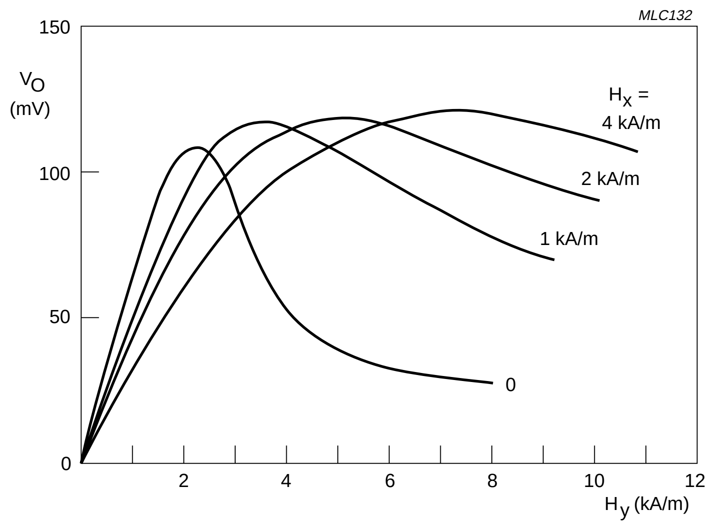

Fig.7 Sensor output 'V_o' as a function of the transverse field H_y.

A Safe Operating ARea (SOAR) can be determined for magnetoresistive sensors, within which the sensor will not flip, depending on a number of factors. The higher the auxiliary field, the more tolerant the sensor becomes to external disturbing fields (H_d) and with an H_x of 3 kA/m or greater, the sensor is stabilized for all disturbing fields as long as it does not irreversibly demagnetize the sensor. If Hd is negative and much larger than the stabilising field H_x, the sensor will flip. This effect is reversible, with the sensor returning to the normal operating mode if H_d again becomes negligible (see Fig.8). However the higher H_x, the greater the reduction in sensor sensitivity and so it is generally recommended to have a minimum auxiliary field that ensures stable operation, generally around 1 kA/m. The SOAR can also be extended for low values of H_x as long as the transverse field is less than 1 kA/m. It is also recommended to apply a large positive auxiliary field before first using the sensor, which erases any residual hysteresis

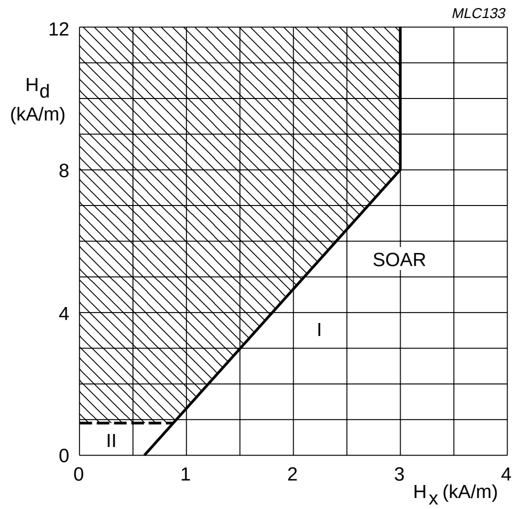

Fig.8 SOAR of a KMZ10B sensor as a function of auxiliary field 'H_x' (MLC133).

APPENDIX 3: SENSOR LAYOUT

In Philips' magnetoresistive sensors, the permalloy strips are formed into a meander pattern on the silicon substrate. With the KMZ10 (see Fig.9) and KMZ51 series, four barber-pole permalloy strips are used while the KMZ41 series has simple elements. The patterns used are different for these three families of sensors in every case, the elements are linked in the same fashion to form the four arms of a Wheatstone bridge. The meander pattern used in the KMZ51 is more sophisticated and also includes integrated compensation and flipping coils (see chapter on weak fields); the KMZ41 is described in more detail in the chapter on angle measurement.

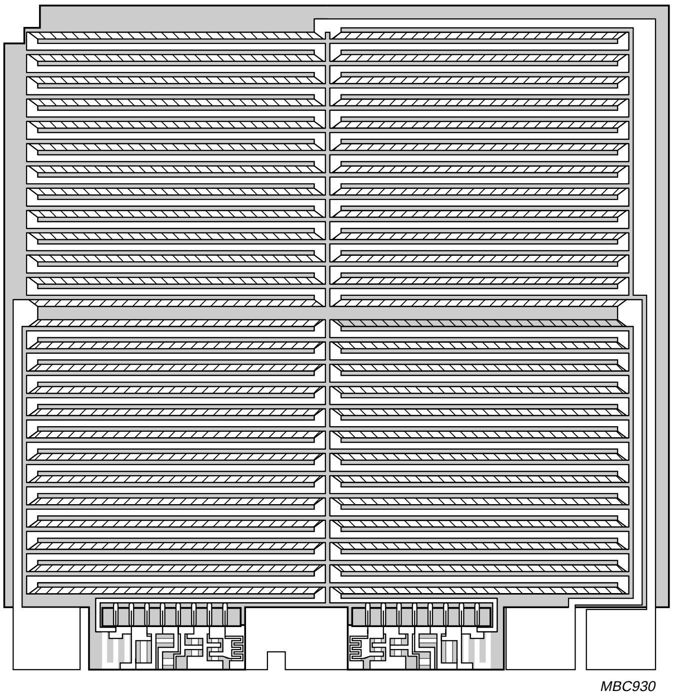

Fig.9 KMZ10 chip structure.

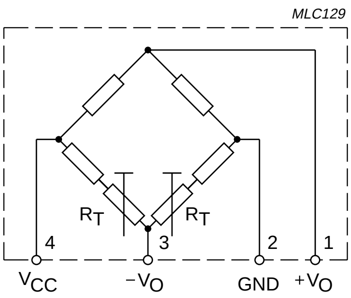

Fig.10 KMZ10 and KMZ11 bridge configuration.

In one pair of diagonally opposed elements the barber-poles are at +45˚ to the strip axis, with the second pair at –45˚. A resistance increase in one pair of elements due to an external magnetic field is matched by an equal decrease in resistance of the second pair. The resulting bridge imbalance is then a linear function of the amplitude of the external magnetic field in the plane of the permalloy strips normal to the strip axis.

This layout largely eliminates the effects of ambient variations (e.g. temperature) on the individual elements and also magnifies the degree of bridge imbalance, increasing sensitivity.

Fig.10 indicates two further trimming resistors (R_T) which allow the sensors electrical offset to be trimmed down to zero during the production process.