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The Role of Solid State Materials in Transducers

Technical Paper 222

By Lewis E. Hollander, Jr. and L. Bruce Wilner

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Reprinted from solid/state/design
November, 1962

Reprinted by Endevco Corporation, Pasadena, California

The increasing knowledge about solid state materials is causing significant changes in the transducer industry. Until quite recently transducers for producing electrical signals from mechanical inputs have required fairly large mechanical motions to obtain detectable electrical signals. Typical were the potentiometer in which increments of resistance were added or removed mechanically, the capacitance gauge in which the plates of a capacitor were moved relative to each other, and the "dynamic" pickup in which a coil was moved in a magnetic field. By and large these transducers used materials which could be regarded as passive, and the transduction could be easily calculated from changes of shape, mechanical displacement, etc.

More recently transducer designs have used solids which are not passive but participate strongly in the transduction. By changing their electrical or magnetic properties with a mechanical or thermal input these materials can provide the active core of a transducer. Temperature transducers employing the large resistance changes of semiconductors are now common, including thermistors, positive temperature coefficient thermistors, sensistors, etc. Mechanical transducers are available which use magnetostostriction, piezoresistance, and piezoelectricity. A number of other effects, including piezocapacitance, magnetoresistance, and piezomagnetism, are under consideration or are in the research and development stages.

The phenomena named above are all bulk effects — i.e., the effects appear throughout the entire volume of solid subjected to the input signal. There are additional solid state effects which are local, being confined to junction areas in diodes and tunnel diodes, active areas in transistors, etc. Some of these local effects are extremely sensitive — e.g., strain gauge factors of many thousand have been observed in tunnel diodes compared with about 150 for bulk semiconductors and two for metal strain gauges. The very large sensitivities of these local effects coupled with the extremely small amount of solid that must be stressed to observe them offer the prospect of controlling relatively large electrical signals with minute amounts of mechanical energy. If these effects can be tamed, the result will be a new class of super-sensors as judged by present standards.

Taming the new effects will not be easy and may never be successful. The requirements a transducer must meet to be marketable read somewhat like the Boy Scout Law: "A transducer is sensitive, linear, rugged, inexpensive, repeatable, stable . . . brave, clean, and reverent." The wide variety of transducers now on the market represents a series of compromises between available transduction techniques and these requirements. Any new transduction effect must survive this compromise and still provide superior performance in order to find a place in the market.

Piezoelectricity

The best established of the solid state transduction phenomena is piezoelectricity. This phenomena was first reported by Nicolson in 1913 as a result of his study of Rochelle salt. Investigation of its application continued at Bell Laboratories with many notable contributions by W. P. Mason. (It is worth noting that Dr. Mason has

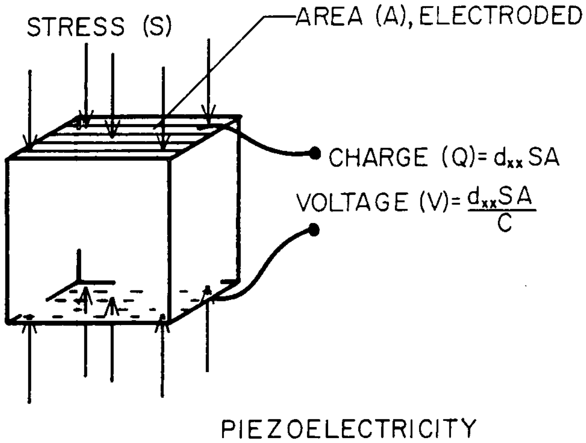

Figure 1 — The coefficient 'd_{xx}' is usually given in coulomb per newton.

not only pioneered piezoelectricity but also piezoresistance and stress effects in tunnel devices.) Drs. Hans Jaffe, A. G. Chynoweth and T. A. Perls have also contributed significantly to the art of solid state transduction.

Piezoelectricity is the generation of a charge separation resulting from mechanical strain (and vica-versa; the effect is reversible).[1] The conversion of mechanical energy to electrical energy is quite efficient, and the voltages developed may be large — e.g., a piezoelectric driver for spark plug ignition is now commercially available (Clevite Corp.). Since all the charge generation is obtained from the mechanical work the charge will leak off with time, seriously limiting low frequency and dc response.

The piezoelectric signal has traditionally been amplified as a voltage appearing across the piezoelectric element. This meant that cable capacitances and amplifier capacitances sharing the generated charge with the piezoelectric element entered into the performance. Recently charge amplifiers have been made available which amplify directly the charge resulting from an applied force, such as Endevco Corp.'s Model 2620 Amplifier, thus increasing the utility of piezoelectric sensors.

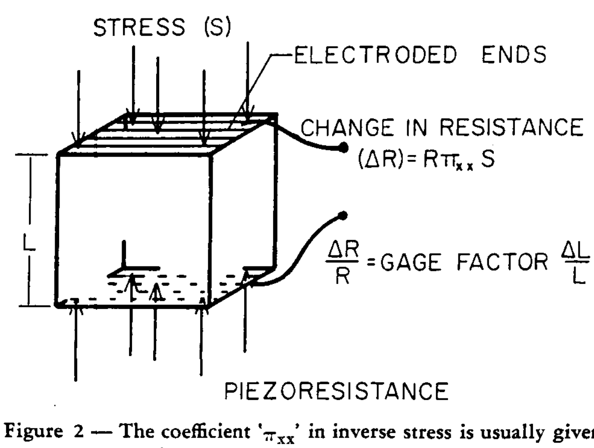

Figure 2 — The coefficient 'π_{xx}' in inverse stress is usually given as cm^2 per dyne.

Materials for piezoelectric devices include single crystal quartz, several other crystals, and a large family of titanates of barium, lead, and zirconium which are used as ceramics, being polarized electrically after fabrication. Because of the efficiency and stability of these materials and their suitability for stiff high frequency transducers, the piezoelectrics have come to dominate the field of shoc[1] and vibration transducers.[2]

Piezoresistance

Piezoresistivity may be defined as a modulation by strain of the conduction mechanisms of a semiconductor.[3,4] In general, the effect is anisotropic, depending in magnitude on directions of stress, current, and voltage relative to a crystal axis. However, large piezoresistance effects can be achieved in polycrystalline semiconductors. Considering only the condition in which current, voltage, and stress are in the same direction (although some of the other arrangements are promising) the effect can be compared directly to wire strain gauges. The gauge factor, which is used as a measure of sensitivity, is the fractional change of resistance, R, (or resistivity, neglecting dimensional changes) divided by the fractional change in length, L.

$$G.F. = \frac{\Delta R/R}{\Delta L/L}$$

For wire strain gauges with negligible modulation of the resistivity the gauge factor runs between 1.5 and 2.1 and results from dimensional changes only. Table I gives a tabulation of gauge factors for some semiconductor materials for which piezoresistance has been reported ir the literature.

The piezoresistive devices which are available at present all employ silicon as the strain sensitive material. Some of the other materials are comparable to silicon in sensitivity, but because of the highly developed technology for working with silicon, any other material would need much greater sensitivity to merit development. Of the other materials reported, gallium antimonide may be of the most immediate interest. In general, for piezoresistive materials from 10 per cent to 80 per cent change in resistance can be expected at yield.

A critical part in the development of piezoresistive transducers has been the achievement of adequate stability. In a device where a 10 per cent change of resistance is full scale, a stability of one part in 10^4 in these resistors is required for a resolution of 0.1 per cent. Thus the problem becomes one of developing solid state resistors which are stable with heat cycling, aging effects, and stress cycling. So far only the more elegant of the silicon piezoresistors have overcome this problem.

Table I also tabulates hydrostatic coefficients for the materials covered. The coefficients are given as 10^{-12} cm^2/dyne; to give the reader a feel for the size of this effect, a coefficient of 200 x 10^{-12} cm^2/dyne is 1 per cent per 750 psi. This large pressure sensitivity offers the possibility of developing a pressure gauge without the usual diaphragm or Bourdon tube type element.

TABLE I

Gauge Factor of Piezoresistive Materials

Material	Type	G.F. Crystal Direction $\frac{\triangle R}{Rx}$	π_h Hydrostatic $\frac{\triangle P}{\rho T}$ 10^{-12} cm²/dyne	Reference
Silicon	p	+175 [111]	4.4	(a)
	n	−133 [100]	+4.6	(a)
Germanium	p	+102 [111]	0	(a)
	n	−157 [111]	16	(a)
Tellurium	p		+250 [001]	(b)
PbTe	p	+30 [111]	+54 [100]	(c)
GaSb	n	−85 [100]	−170	(d)
TiO_2	n	+28 [001]	32 [100]	(e)
$Bi_2 Te_3$	p	+87 [0001]	−40 [0001]	(f)
GaAs	p	+30 [100]	−12	(g)
InSb	p	−45 [100]	−260	(a)
	n	−75 [100]	−190	(a)
$BaTiO_{3-x}$ (Ceramic)	n	+150	+105	(h)
Pyrolytic-Graphite	—	+ $\simeq$ 10-30	+20 [c-axis]	(i)

(a) See Reference 3.
(b) Long, D., *Phys. Rev., 101,* 1256, 1956.
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(i) Private communication.

In contrast to piezoelectric elements, a piezoresistive element derives its power from an external electrical source. Thus the signal from a piezoresistive transducer will persist as long as the mechanical input persists making static (dc) measurement possible.

Local Effect Phenomena

The effects occurring in special areas within semiconductors are significantly more sensitive than bulk effects. These effects seem associated with the possibility of passage of carriers through a barrier, and since only the barrier need be stressed to achieve control of relatively large electrical power, they offer gain in the electronic sense. Most of the effects observed thus far are very temperature dependent, and some are unstable with time. If these and other problems can be overcome, the local effects will make possible transducers of far greater sensitivity than are available at present.

A large pressure effect in tunnel diodes has already been demonstrated by Sikorski and Mason at Bell Labs. In terms of gauge factor, this effect is about 20 times the bulk piezoresistance in silicon. A number of other junction and majority carrier devices exhibit extremely large parameter changes when strained and might be utilized as high

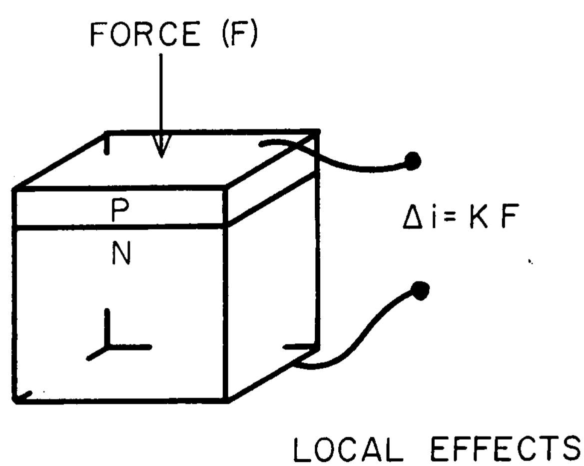

Figure 3 — The coefficients differ for different effects, and their relations are still being determined.

gain sensors. Silicon P-N junctions exhibit an effect which appears to be exponential with strain. Thus large strains are required for observable effects, but very large parameter changes are possible. The non-linearity and extreme temperature dependence suggest that simple P-N junction devices will not have a very bright future. Tunnel devices are restricted electrically to the 0.1 to 0.5 volt range where negative resistance occurs restricting the potential of transducers based on this phenomenon. Majority carrier devices are not so limited electrically, and their strain sensitivity seems linear, but too little research has been done to define their potential for transducers.

Conclusions

Solid state technology will inevitably find increasing application in the transducer industry. The piezoelectric effect has been widely adopted and successfully employed for dynamic transducers. Piezoresistive transducers using silicon are now being offered on the market, and more sophisticated versions are being planned. The next major development will be in the utilization of the newer "local" effects which offer extremely large sensitivities.

The 1961 market for transducers was estimated as $101 million with a projected growth to $150 million in 1965.[5] It is possible new developments may accelerate the growth of this market by 50 per cent, partly at the expense of the amplifier market and partly by offering capabilities never before available. In transducers, as in several other rapidly moving technologies, the key problems are those associated with the materials, and the richest rewards may be expected to go to those with the grestest materials competence.

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TP222-011922