Reprinted from IEEE TRANSACTIONS
ON *INDUSTRIAL ELECTRONICS AND CONTROL INSTRUMENTATION*
Volume IECI-16, Number 1, July, 1969
pp. 40-43

Piezoresistive Force Gauges and Their Uses

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***Abstract*—A sensitive and efficient piezoresistive element is described. It is constructed of *p*-type silicon mounted on an electromechanical substrate, and thus is easy to handle and apply where the measurand can be reduced to a force of about 10 grams. This device, the PIXIE, is linear, low noise, relatively inexpensive, and can stand large overloads.**

INTRODUCTION

A PIEZORESISTIVE device with very high sensitivity, low noise, good linearity, and moderate and predictable temperature coefficients has been developed. The material chosen for this device is *p*-type silicon, with stress, current, and voltage all in the 111 crystal direction. The device is so shaped that all the stress and all the resistance occur in a section with dimensions as small as we can economically control. The semiconductor is mounted on an electromechanical substrate affording easy electrical and mechanical connections.

The device can be used directly in audio frequency applications, such as phonographs and microphones. Its moderate impedance, all resistive, makes a good match to transistors and offers excellent frequency response throughout the audio range. Used in matched pairs to compensate resistance change with temperature, the devices form the basis for transducers with high output and frequency response from steady state to 6 kHz or higher.

MATERIAL FOR PIXIES

The piezoresistive material used in the transducers is lightly doped *p*-type silicon. A variety of considerations were involved in material selection, and in all of them, silicon is either at the top of the list or high on the list. First consideration, of course, is piezoresistivity. One pertinent measure of piezoresistivity is the gauge factor, resistivity change per unit strain. Silicon tops the list of common semiconductors with a gauge factor of 175 for lightly doped *p*-type material with current, voltage, and strain all in the 111 crystal direction. *N*-type germanium and reduced $BaTiO_3$ are close runners-up at 150.[1] By varying the doping level, some of silicon's gauge factor can be traded for temperature insensitivity and low noise levels, but the lightly doped value is valid for making the comparison.

A second virtue sought in a piezoresistive material is availability of the material itself and of the technology for processing it. Here again, silicon tops the list. Although we have had to develop some proprietary art in processing the silicon, the material itself is a commodity in an open and competitive market, and the transistor people have provided a vast store of information on the fabrication and physics of silicon.

Thirdly, the piezoresistive material should be strong enough to provide a large signal (resistance change) from its gauge factor, and some safety factor over the measured load. Here silicon carbide tops the list, but silicon is more than adequately strong, with specimens commonly exceeding $\frac{1}{2}$ million psi stress, or 2 percent strain. Silicon is brittle, but this is inherent in crystalline semiconductors and brings with it the advantage of freedom from hysteresis.

Other virtues sought are predictability of thermal performance, wide temperature range, ease of making ohmic electrical contact, stability of resistivity, etc., and in all of these, *p*-type silicon compares well with other piezoresistive materials.

THE CONFIGURATION

In devising a semiconductor piezoresistive element for transducers, one must balance performance against ease of fabrication and of application. The measure of performance we have used is the ratio of signal power produced to strain energy applied. These are the true output and input of any non-self-generating transducer; a static work input is used to modify the flow of externally applied power and divert some of it to the signal channel.

To minimize strain energy for a given level of strain (and therefore resistance change), the smallest possible amount of material should be strained. In order not to strain inert substrate material, the piezoresistor should be unbonded (in contrast to bonded strain gauges). Only the piezoresistive material should be strained, and as little as possible of that. The resistance-change signal results from a state of strain in the material. A limited amount of strain energy produces a higher state of strain in a small volume of material than in a larger volume. To maximize signal power for a given level of strain and resistance change means simply maximizing the bias power in the piezoresistor. To do this in a material with steep temperature coefficients calls for good heat sinking, but we have just established that the piezoresistor should be unbonded, so the heat sinking must be through the bonded ends only. Thus, the lengthwise heat paths in the piezoresistor should be as short and fat as possible. The outcome of this is that

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Manuscript received December 16, 1968. This paper was presented at the IEEE Transducer Conference Washington, D.C., February 10-11, 1969.
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[1] L. E. Hollander and L. B. Wilner, "The role of solid state material in transducers," *Solid-State Design*, vol. 3, November 1962.

the most efficient piezoresistor is an unbonded segment of vanishingly small volume, especially of short length, closely coupled at its ends to good heat sinks. This is the ideal we have tried to approach. The piezoresistor design is two relatively large endblocks joined by a short, narrow neck.

The neck is about 0.001×0.007 inch cross section by about 0.005 inch long. These "large" dimensions are concessions to the need for easy dimensional control. All the action—the resistance and the strain—takes place in the neck. The endblocks are merely handles for making electrical, mechanical, and thermal contact, and for handling.

The very short length of the active section provides a second benefit in addition to heat sinking. It is impossible to collapse the active section as a column; therefore, the strength of the piezoresistor in compression is the crushing strength of silicon, something near a million psi. A filamentary unbonded gauge would buckle at a compressive stress level of a few thousand psi.

THE MOUNTING

In order to use the piezoresistor, it must be electrically connected to a measuring circuit and mechanically connected both to the mechanical input and to a heat sink. We make both of these connections at once by soldering the piezoresistor down onto a 10:1 lever. The substrate lever is a long rectangular bar with a deep transverse notch across which the piezoresistor is soldered. See Fig. 1. The material remaining at the bottom of the notch serves as an elastic hinge around which the halves of the bar can be regarded as pivoting. The top and bottom surfaces of the bar and one end are conductors. The other end and the notch are electrically open. The open end of the substrate affords connection to both ends of the piezoresistor. When the open end of the substrate is grasped between two conductors leading to a readout system, the grasping can provide both mechanical mounting and electrical connection to the piezoresistive assembly. Input force loads are then applied to the conductive end of the substrate in such a way as to cause rotation around the elastic hinge at the bottom of the notch.

For most applications, an epoxyglass copper substrate is used. This is the same material used in printed circuit boards. It is available and familiar, and is readily processed to the required electrical and mechanical configuration. It is both sturdy and malleable in the hands of the user. With adequate protection for the solder bonds to the die, the epoxyglass copper substrate is readily solderable. It is quite an adequate substrate for audio signals, for small static signals, or for large static signals of less than a minute duration. Under large steady-state loads, its malleability begins to show; the epoxyglass will creep.

The epoxyglass copper substrate is relatively flexible. The flexibility reduces its free resonance. Its resonant frequency mounted but not loaded is only 6 kHz. However, by clever loading and damping, users are making instruments flat to 20 kHz.

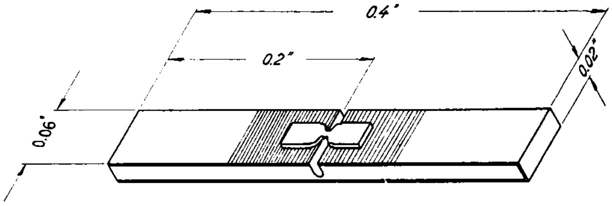

Fig. 1. The Pixie transducer, a silicon stress gauge on its substrate.

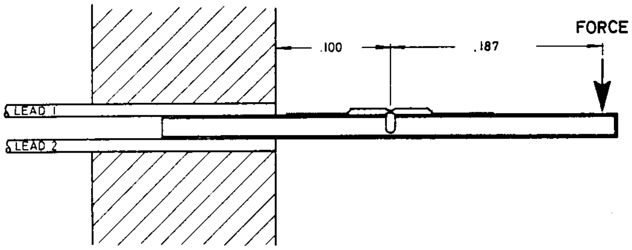

Fig. 2. Conventional mounting and loading pattern for the Pixie.

For applications requiring either large static load or high efficiency or high free resonant frequency, we have devised a substrate of alumina ceramic with thick-film conductors. Because of the need for a notch-bottom hinge, this substrate is frustratingly difficult to fabricate. But it rewards us with no creep that we can detect, three times the efficiency of epoxyglass, and a free resonant frequency around 10 kHz.

THE PERFORMANCE

The performance of the PIXIE®[2] on an epoxyglass substrate is somewhat better than comparable piezoelectric ceramics over most of the audio frequency range, and, of course, incomparably better at very low frequencies. Conventionally mounted and stressed (see Fig. 2), a one gram load will give a resistance change of 1.6 percent. If the PIXIE is 1600 ohms and is excited by 7.5 mA from a high impedance source (12 volts on the PIXIE), the signal is 192 mV with an apparent signal power of 23 μW (6 μW into a matched load). The input point displaces 1.4 micron, requiring 0.077 ergs input energy. If this same energy were applied to a piezoelectric with a conversion efficiency $k=0.1$, it would give 8×10^{-10} Ws peak signal energy, and the signal power would be comparable to the PIXIE only at 2.5 kHz and above. The PIXIE on ceramic compares even more favorably with piezoelectrics.

The PIXIE has a substantially linear resistance change with applied force from -15 percent resistance change to $+15$ percent resistance change, approximately ±10 grams force. At greater applied loads, the

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[2] PIXIE is a registered trademark and devices are covered by U. S. Patent 3 351 880.

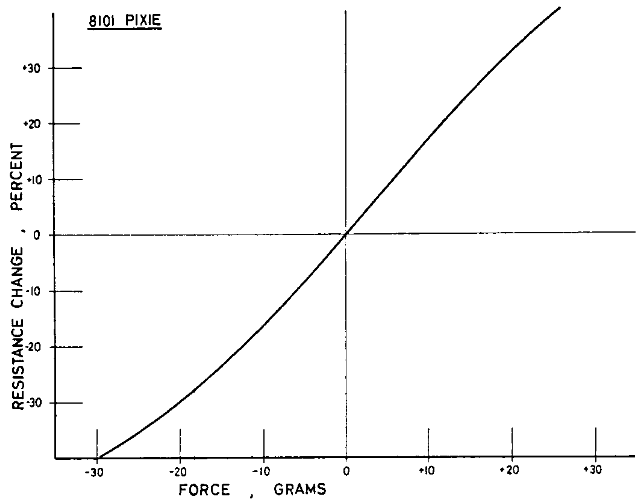

Fig. 3. Typical transfer curve for a Pixie showing linearity around zero.

sensitivity declines, giving an *S*-shaped transfer curve (see Fig. 3). The devices are proof-tested to 40 grams in the direction stretching the semiconductor, at which load the resistance change is about +45 percent. They are generally much stronger in compression and at −80 grams show resistance changes of the order of −60 percent. Using the constant current source mentioned earlier (7.5 mA, 1600 ohms, 12 volts), the linear range of the PIXIE gives a ±1.8-volt peak signal, 1.27-V rms. The noise under these conditions is of the order of 3.6 μV rms in an audio band 3 kHz ± 1.5 kHz, indicating a dynamic range of 111 dB.

The thermal performance of the PIXIE is just that of *p*-type silicon, which is not so spectacularly good as the transfer curve. The resistance changes with temperature at a rate of ±0.67 to 0.74 percent per °C. The sensitivity changes with temperature at a rate of −0.22 percent per °C. The large temperature coefficient of resistance can be neutralized in a system by pairing PIXIEs as adjacent legs in a Wheatstone bridge. This is especially effective if the PIXIEs are carefully matched. We routinely build transducers with pairs matched to 3 parts per 1000 over a 100°C span. The positive coefficient of resistance can be used to offset the negative coefficient of sensitivity if the devices are powered by source of finite impedance. In practice, we build half Wheatstone bridges in which we add to each piezoresistive leg a series resistor about one-half the room-temperature resistance of the semiconductor. This gives adequate sensitivity compensation for ±75°C around room temperature.

The PIXIE's upper temperature limit is set by solder and substrate. For epoxyglass substrates, it is about 200°F, for ceramic, about 300°F. The lower limit has not been established. We routinely test to −11°F. We know the PIXIEs are functional at −65°F. We have not sought information colder than −65°F.

Comparison to Other Devices

To demonstrate the virtues (and limitations) of this unbonded piezoresistor concept, it is instructive to make some comparisons to alternative transduction systems.

For audio transducers, the alternative is a laminated piezoelectric ceramic structure. These characteristically give a high output voltage from a high impedance. A laminate of the same dimensions as a PIXIE had a capacitance of 560 pF, and gave an output of 1.72 volts per gram (compared to 192 mV previously cited for PIXIE). The impedance of the laminate varies as $\frac{1}{2}\pi fC$, is 3 MΩ at 100 Hz, 300 kΩ at 1 kHz. The equivalent power (V^2/impedance) is less than that of the piezoresistor at all frequencies less than 3.5 kHz. At zero frequency (steady load), the impedance of the piezoelectric laminate is infinite and its output power is zero. Piezoelectrics do not work for measuring steady loads.

For low-frequency or steady-state measurements, other nonself-generating transducers are considered: potentiometers, linear variable transformers, variable capacitors, unbonded wire strain gauges, and bonded strain gauges. Pots are unequalled for signal power. Apparent signal power can be 100 percent of bias power, a watt or more compared to 3 percent of a one-half-watt bias power on a full bridge of PIXIEs driven to ±17 percent resistance change. Pots, however, require relatively large input energy to drag the wiper, and pots are always pinched between a few million cycles of life and a few ohms of wiper noise, neither of which bother a piezoresistor.

Variable capacitors, LVT's, and variable reactors are theoretically capable of higher output/input and signal/noise ratios than piezoresistors, but are utterly dependent on the quality of driver and detector apparatus and the cabling connecting them to it. More complexity and precision is required of a system employing reactive transducers than of one employing resistive transducers. A solution of a measurement problem is more simply achieved with a piezoresistor than with, say, a variable capacitor.

A well-made device using unbonded wire strain gauges can have a smaller volume of stressed material than a PIXIE, but the far higher gauge factor of silicon still gives PIXIE a 50 to 1 advantage in output–input. Further, the PIXIE will stand at least a four times overload beyond its linear range, while overranging for unbonded wires is usually cited in percent. Perhaps most important, the making of unbonded wire strain gauge transducers is an exquisite art, not to be dabbled in by the uninitiated.

Bonded piezoresistive strain gauges can produce levels of signal, signal to noise, and overrange, similar to the PIXIE. However, the substrate to the bonded gauge must be stressed to the same stress level as the gauge, so the input energy for the same output power is far greater. Where input energy is unlimited, the choice becomes one of cost and convenience.

Some newer solid-state devices produce signal levels greater than silicon piezoresistors. There is a semiconductor rubber available which can be driven over a factor of 10 in resistance. It still requires a lot of energy in per unit power out, and has the problems of creep and stability which are normal to rubber. A large number of stressed junction semiconductor transducers have been published. At present, only one is commercially available, a needle bearing on the emitter of a transistor. Its sensitivity (output/input) is marvelously large. So are its thermal effects and noise. The fact that it is a transistor is somewhat restrictive to the circuitry in which it can be used. The simple resistive character of a PIXIE is easier to apply.

THE USES

The uses of the PIXIE are as varied as the needs for transducing mechanical information to electrical. The highest volume of use is in phonograph cartridges where the needle is coupled to the PIXIE tip with a rubber yoke. The ability of the PIXIE to respond down to zero frequency offers splendid bass response. Endevco uses PIXIE internally as components in accelerometers and pressure transducers. An accelerometer can be simply a matched pair of PIXIEs with weights on their input ends. A pressure transducer is more complex in that pressure must first be converted to force by a piston then the force imposed on a PIXIE pair through a linkage. Similar linkages give us paired-PIXIE force transducers, and linkages and springs lead to displacement transducers.

These devices are also used as null detectors in servo systems, as the active elements in microphones, and as the weighing elements in liquid density meters. In one interesting application, the PIXIE is attached to a piece of humidity-sensitive fiber to form an electrical hygrometer.

Some of the wilder applications we have heard about are in the life sciences. An entomologist who was studying communication between ants, caused ants to stand on the end of a PIXIE so he could listen to the sounds of their creaking joints. Several physiologists have stitched PIXIEs onto heart walls to study heart muscle forces and experimental changes in the heart muscle. Obstetricians talk of taping PIXIEs on the abdomen of a woman in labor to monitor the contractions.

CONTINUING DEVELOPMENTS

Development work is continuing within the framework of a force-variable resistor. We have means of varying the unstressed resistance over wide ranges, and we have means of changing the temperature coefficient of resistance, and to some extent, the temperature coefficient of sensitivity.

Modifications have been made to give more power handling capability (and less sensitivity) and more sensitivity (with less power handling capability).

Substrates have been varied in material, thickness, width, and length. We have a very thin epoxyglass substrate which gives 15 percent resistance change at 3 grams rather than at 10 grams, but which deflects 0.005 inch at 3 grams rather than 0.0005 inch at 10 grams. We have a substrate capable of applying 150 grams to a die, steady-state, either direction. Now we are working on a semiconductor die which needs so excellent a substrate.

CONCLUSION

We have developed a very sensitive, very efficient piezoresistive element. We have mounted it on a combination electrical–mechanical substrate which makes it relatively easy to handle and easy to apply where the measurand can be reduced to a force of about 10 grams. The device is linear, low noise, and stands large overloads. And it is relatively inexpensive.