

FINAL REPORT ON

RESEARCH ON PRESSURE SENSORS
FOR BIOMEDICAL INSTRUMENTS

PERFORMED ON

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ABSTRACT

A four-year research program which began in October 1969 led to the development of a piezo-resistive pressure transducer suitable for recording pressures typically encountered in biomedical applications. The pressure transducer consists of a thin silicon diaphragm containing four strain-sensitive resistors, and is fabricated using silicon monolithic integrated-circuit technology. Pressure-induced stress in the diaphragm is sensed by the resistors, which are interconnected to form a Wheatstone bridge.

The pressure transducers can be as small as 0.7 mm outer diameter, and are, as a result, suitable for mounting at the tip of a catheter. Because of the work achieved on the grant, additional programs to further develop the pressure transducer have been established, and a licensing agreement has been signed with Cordis Laboratories Inc. of Miami, Florida to apply the principles of the sensor in a commercially available catheter.

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RESEARCH ON PRESSURE SENSORS FOR BIOMEDICAL INSTRUMENTS

I. Introduction. This report covers the research on the development of a silicon-diaphragm pressure transducer which was begun on October 1, 1969 and concluded on September 30, 1973. The program resulted in the first version of a very successful series of pressure transducers, on which development has continued for a variety of biomedical applications. The principal work conducted on the grant resulted in a publication which appeared in the March, 1973 issue of the IEEE Transactions on biomedical engineering. Because this publication thoroughly describes the work on this phase of the grant, it is incorporated into this report as ~~Appendix~~ ^{Reference} I. This paper was based on the Ph.D. dissertation of one of the authors, Samaun, which was accepted by Stanford in August 1971.

The other phases of the project were less intensive than the work of Samaun and are reported below. First was an attempt to develop a two-lead pressure transducer which would reduce from four to two the number of connections which must be made to the small pressure transducer. Second was the attempt to use ion-implantation to form the strain-sensitive resistors, in order to provide much higher resistance values, so that short circuit currents which might result from rupture of the diaphragm could be kept low enough to avoid any threat of lethality or damage to the biological environment in which the sensor was used.

II. The Successful Pressure Sensor. A thin-diaphragm piezoresistive pressure sensor for biomedical instrumentation has been developed using monolithic integrated-circuit (IC) techniques. The piezoresistive effect has been chosen for this device because it provides an observable resistance change that is a linear function of pressure and is observable at low stress levels. A diaphragm is used as a stress magnifying device; its magnification is proportional to the square of the ratio of the diaphragm diameter to its thickness. The pressure-induced stresses in the diaphragm are sensed by properly oriented piezoresistors interconnected to form a bridge.

An anisotropic etching technique is used for the formation of the diaphragms; this technique makes possible a novel thickness monitoring scheme that also acts as a chip separation etch. Sensors with diaphragm diameters of 0.5 mm and thickness of only 5 μm , surrounded by a 0.15 mm wide ring of thick silicon, have been batch fabricated using this technique. An intrinsic sensitivity of 14 $\mu\text{V}/\text{V}$ supply/mmHg has been achieved.

Temperature drift in these sensors is dominated by the temperature dependence of the piezoresistive coefficient. A temperature-compensation circuit has been devised for these sensors by deriving a temperature-dependent signal that is pressure independent for the compensation of the temperature-dependent part of the bridge unbalance voltage.

These sensors, after being mounted on the tip of a small catheter, can be inserted into the biological system through the inner bore of a larger catheter

that was formerly occupied by a guide wire. The sensors have been utilized for acute measurements of blood pressure in dogs with satisfactory results.

Details of this structure have been published.¹ The article is incorporated in this paper as Appendix I. Prior to the publication of this paper, an abridged version was presented at the 1971 IEEE International Solid-state Circuits Conference,² and is included in the digest of technical papers of that conference.

III. A Two-Lead Pressure Transducer. The pressure transducer described in Appendix I requires four leads for making connection to the four corners of the Wheatstone bridge in the transducer. Because it is difficult to make dependable connections to such a small structure, it was deemed desirable to attempt to develop a two-lead version, as shown schematically in Figure 1. In this version, a bridge consisting of two diodes and two resistors is driven by a ac source through a capacitor. If both resistors have exactly the same value, no dc voltage is developed on the capacitor. However, if the resistors are unequal (for example, if they were changed by pressure induced stress in the diaphragm, then more current flows during one-half of the ac waveform than during the second half.) Thus, a direct voltage will be developed on the capacitor. This direct voltage can be measured by a low-frequency detector which does not respond to the a-c sensing signal. As a result, only two leads (such as a coaxial cable or a highly flexible twisted pair) are needed to connect to the transducer.

Initial fabrication attempts indicate that a pressure transducer can be fabricated using the above principle to reduce the required number of leads. However, this work could not be carried far enough, during the conduct of this research work, to result in a usable design.

IV. A Completely Safe Transducer. The pressure transducer fabricated as described in Appendix I using diffused p-resistors as the strain-sensitive elements. With thermal diffusion as the means of introducing the doping, it was found that a sheet resistivity of the order of 100 ohms/square is optimum. As a result, these resistors run in the range of 2-5 kilohms.

Because sensing voltages must be of the order of one to ten volts applied to the bridge, in order to obtain good signal-to-noise ratio at the output of the bridge, short-circuit currents with a diffused-resistor bridge are of the order of 0.1-1.0 ma, which is high enough to be of some concern in certain biomedical applications. On the other hand, a short-circuit current of 10 μ a is considered completely safe in all circumstances. Thus, if the resistors' values can be increased by a factor of 30 to 100, a completely safe pressure transducer will result. Because ion implantation can be used to provide carefully controlled layers of impurity dopants with much smaller total concentration than thermal diffusion, attempts were made to fabricate four-resistor diaphragms with sheet resistivities of 5,000 ohms/square. The two such implantations that were tried were successful in that the desired resistance range was achieved. However, the yields in processing the structures so formed into thin diaphragms, together with subsequent mounting, were low enough that no successfully mounted structures could be evaluated in vivo.

V. Continuation Work. Although the work supported by this grant was ended in 1973, work on such pressure transducers has continued with support from the National Institutes of Health. The major development in this continuing work has been to perfect an absolute pressure transducer, in which a glass cavity is hermetically sealed to one side of the pressure sensitive diaphragm to provide a reference pressure. The current model consists of a glass cap that has a well etched in it and a silicon diaphragm containing four diffused piezoresistors connected to form a Wheatstone bridge. A cross section of this structure is shown in Figure 2.

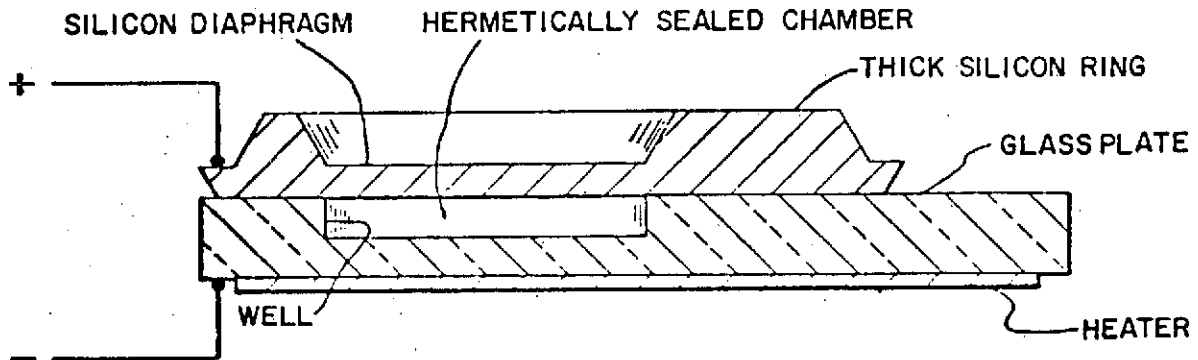


FIGURE 2 -- ABSOLUTE-PRESSURE TRANSDUCER STRUCTURE

The diaphragm is surrounded by a thick rim of silicon for support and protection. To construct the absolute pressure transducer, the glass cap with the well positioned directly over the diaphragm is anodically bonded to the silicon rim. The anodic bond is accomplished by heating the glass and silicon to 400°C and then applying a potential of 600 V to the silicon with the glass cap grounded. The bond is hermetic, and thus the well and diaphragm now form a hermetically sealed chamber with a predetermined pressure trapped therein.

The diaphragm contains integrated-circuit resistors that form elements of a Wheatstone bridge. Their values change as the diaphragm flexes. A patent application has been signed to protect various aspects of this structure. Cordis Laboratories of Miami, Florida has signed a license agreement with Stanford University to use this technique for making pressure transducers in the fabrication of pressure cells to be incorporated in the wall of a catheter.

Several of these absolute pressure transducers have been developed and tested. The overall dimensions are 1.5 x 2.0 x 0.2 mm. They have an intrinsic sensitivity of 30 $\mu\text{V}/\text{mmHg}/\text{V}$ supply and a temperature drift equivalent to

-2 mmHg/°C. The output voltage is linear with pressure for changes up to 300 mmHg. Our current work is aimed at investigating different techniques for reducing the temperature drift.

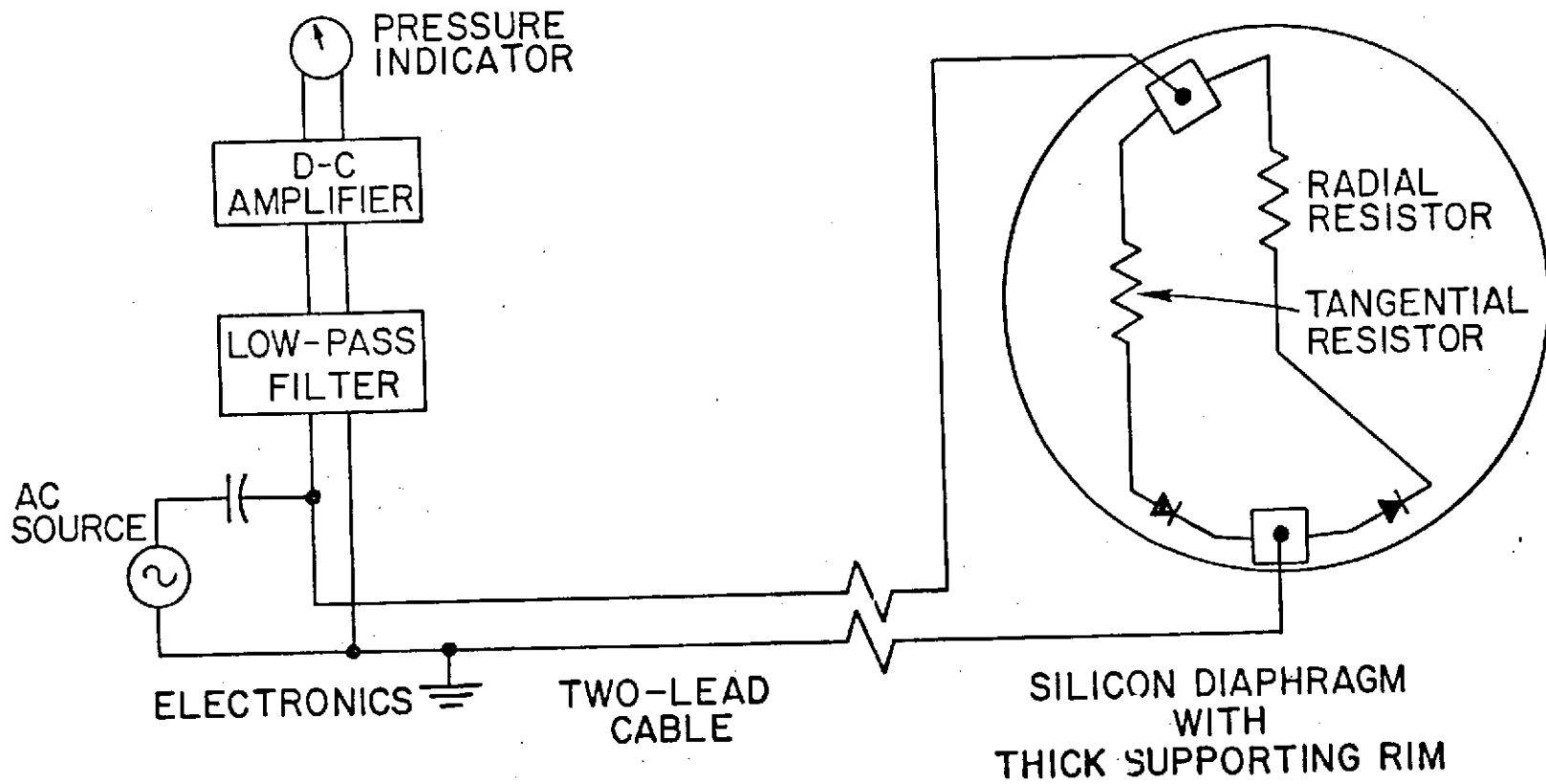


FIGURE 1 -- TWO-LEAD PRESSURE TRANSDUCER

REFERENCES

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- 1) Samaun, Kensall D. Wise, and James B. Angell, "An IC Piezoresistive Pressure Sensor for Biomedical Instrumentation", IEEE Transactions On Biomedical Engineering, Volume BME-20, No. 2, pp. 101-109, March 1973.
- 2) Samaun, K.D. Wise, E.D. Nielsen, and James B. Angell, "An IC Piezoresistive Pressure Sensor for Biomedical Instrumentation", Digest of Technical Papers of the 1971 IEEE International Solid-state Circuit Conference, pp. 104-105, February 1971.
- 3) Most of the conduct work on this development has been supported by NIH Contract 70-2557 and N01-HD3-2774 entitled "Physiology of the Oviduct," with support for certain phases being provided by Integrated Electronics for Medical Applications" NIH Grant 5 P01 GM17940-05