Pressure Transducer with Au–Ni Thin-Film Strain Gauges

K. Rajanna, S. Mohan, M. M. Nayak, N. Gunasekaran, and A. E. Muthunayagam

Abstract—The behavior of a pressure transducer with Au–Ni (89:11) film as strain gauges have been studied. The effects of post-deposition heat treatment on the resistance of the thin-film strain gauges and hence the output performance of the pressure transducer are discussed. The effect of a repeated number of pressure cycles carried out over a period of eight months has also been reported. The maximum nonlinearity and the hysteresis is improved from 0.92% FSO to 0.06% FSO after 1000 pressure cycles. The output behavior of the pressure transducer with temperature has also been studied.

I. INTRODUCTION

PRESSURE transducers are basically electromechanical devices used for a variety of applications. The primary function of the pressure transducer is to sense fluid pressure and provide an electrical output proportional to the input pressure. A pressure transducer essentially consists of a diaphragm which undergoes deformation due to a strain gauge bonded to it. It was more common to use foil-type strain gauges for this purpose. However, in recent years, the use of thin-film strain gauges as sensors in pressure transducers has gained importance due to their numerous merits. The distinct advantages are absence of adhesive material, flexibility to tailor the properties of the sensing film, etc. Although several investigations on the strain sensitivity of different metal [1]–[16] and alloy films [17]–[19] have been reported, the publications on the utility of these films as strain gauges in devices such as pressure transducers are few.

In the present paper we report the study of a pressure transducer with Au–Ni (89:11) alloy thin-film strain gauges with a meandering pattern [15].

The starting material for fabrication was Au–Ni (82:18), a high-temperature brazing alloy with a unique characteristic, namely, its liquid and solid temperatures are the same (950°C). Although this alloy is being used for brazing of stainless-steel foils, it is found to have very good adhesion and corrosion resistance properties [20]. In view of these and since no study of this alloy with respect to strain gauges has been reported, an attempt to explore its suitability and applicability for thin-film strain gauge application has been made in the present work.

II. EXPERIMENTATION

In the present work an integrated diaphragm assembly has been employed. A special feature of this diaphragm design is the incorporation of a strain-relieving cavity to take care of the strain due to mechanical handling, mounting, or assembly process. The material used for the fabrication of the pressure transducer is precipitatively hardened X17U4 steel. Further, details including the dimensions of the diaphragm assembly and the information on diaphragm surface preparation are given in our earlier publication [21]. Before depositing the sensing film (strain gauges), the insulating films consisting of alternate layers of Al2O3 and SiO2 were deposited on the diaphragm surface using reactive electron beam evaporation technique. The diaphragm assembly was maintained at 200°C during deposition. The need to deposit insulating oxide layers, the deposition process details, and the necessity to have multilayers instead of single-layer oxide films have already been described by Rajanna et al. [21].

After the deposition of the insulating oxide layers, copper contact pad films and interconnecting copper pad films of thickness greater than 3000 Å were deposited. Subsequently, Au–Ni film (strain gauge film) was deposited. The Au–Ni (82:18) material in the form of wire (obtained from Wilkinson Company, USA) was evaporated from a molybdenum boat. It is believed that since gold and nickel possess nearly the same vapor pressures at a given temperature, the possibility of fractionization of this alloy during evaporation is much smaller. In order to minimize the possibility of fractionization, a shutter was placed above the source during initial heating of the boat. The shutter was removed only when the boat temperature was sufficiently high to evaporate both the constituents of the alloy. The boat temperature during the evaporation was close to 1200°C. The analysis of the deposited film by plasma emission spectrometry technique revealed the Au–Ni composition as 89.2%: 10.8%. This deviation in composition from starting material is attributed to the fact that single-source evaporation of a composite containing two or more components results in incongruent evaporation
A. Effects of Post-Deposition Heat Treatment on the Thin-Film Strain Gauge System

As can be seen in Table I, the post-deposition heat treatment resulted in a decrease in gauge resistance. The reduction in gauge resistance is attributed to annealing of defects incorporated in the film structure during deposition [24], [25]. It is important to note here that whereas the manganese film pressure transducer [23] had an average reduction of 6.5% in gauge resistance after heat treatment at 120°C, the average reduction achieved in the present Au-Ni film resistance was only 9.29%. Therefore, in order to make sure of the almost complete annealing of defects, the heat treatment process was repeated at 170°C. After the second heat treatment, the average decrease in gauge resistance was 1.36%. However, further heat treatment did not result in any additional decrease in gauge resistance.

TABLE I

<table>
<thead>
<tr>
<th>Details of the Thin-Film Strain Gauges</th>
<th>Before Heat Treatment</th>
<th>After Heat Treatment at 120°C for 1 h</th>
<th>After Second Round of Heat Treatment at 170°C for 2 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauges located at the edge of the diaphragm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gauge T1</td>
<td>105.79</td>
<td>105.45</td>
<td>106.68</td>
</tr>
<tr>
<td>gauge T2</td>
<td>104.92</td>
<td>104.78</td>
<td>104.00</td>
</tr>
<tr>
<td>Gauges located near the center of the diaphragm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gauge C1</td>
<td>96.58</td>
<td>96.17</td>
<td>94.50</td>
</tr>
<tr>
<td>gauge C2</td>
<td>99.59</td>
<td>99.31</td>
<td>98.23</td>
</tr>
</tbody>
</table>

The insulation resistance of the oxide layers increased from about 300 to 40 000 MΩ at 10 V dc due to post-deposition heat treatment. The increase in insulation resistance is believed to be due to enhanced oxidation of the individual oxide layers and the formation of stronger interfaces between layers.

B. Individual Gauge Response

Figs. 2 and 3 show the variation of relative change in resistance $\Delta R/R$ with pressure for the gauges ($T_1$ and $T_2$) located near the center of the diaphragm and those at the edge ($C_1$ and $C_2$) after the post-deposition heat treatment. It is observed that for all the gauges, the variation in $\Delta R/R$ with pressure is more linear and repeatable (between gauges) after the heat treatment process when compared to the variation of the same before the heat treatment.

C. Output Performance of the Thin-Film Pressure Transducer

The variation in output voltage of the pressure transducer as a function of input pressure is quite linear. The values of non-linearity and hysteresis (in percentage FSO; full scale output) versus pressure (in bars) are shown in Fig. 4. The maximum nonlinearity and hysteresis observed is 0.92% FSO. By considering the resistance of the thin-film strain gauges, the film thickness, the power dissipation factor, etc., the bridge excitation was optimized to 3 V dc. It has been observed that higher excitation voltages showed instability above 1% of FSO in the output of the pressure transducer under zero load condition. This instability at higher excitation voltages is considered to be due to excessive heating of the thin-film strain gauges.

Further, it was found that the nonlinearity and hysteresis improved after 1000 pressure cycles of a nominal pressure of 30 bar for 3-min duration carried out over a period of 8 months. The typical data of maximum non-linearity and hysteresis observed after 500 cycles is 0.39% FSO. Again the maximum nonlinearity and hysteresis found after additional 500 cycles is 0.06% FSO. This indicates that films require about 1000 cycles to achieve nonlinearity and hysteresis of the order of 0.06%, which

Fig. 1. Thin-film strain gauge pattern deposited on the pressure transducer diaphragm.

The thickness of the Au-Ni film (650 Å) during deposition was measured and later compared using a multiple beam interferometer. Prior to deposition of copper and Au-Ni, the substrate was subjected to ionics cleaning for about 10 min. Precision mechanical masks were used while depositing the above films of required pattern. These masks were prepared using a CNC (Computer Numerically Controlled) spark erosion machine with a dimensional tolerance of ±1 μm. The strain-gauge pattern adopted (for the four gauges, as shown in Fig. 1) and their location on the diaphragm are the same as those already reported in our earlier paper [23].

The four gauges were connected in Wheatstone bridge configuration with all active gauges. The gauges experiencing the tensile strain near the center) are connected in one set of opposite arms and those experiencing the compressive strain (at the diaphragm edge) in the other. It is important to note that the tensile strain causes the resistance of the gauge to increase and compressive strain results in decrease of resistance. The stabilization of the film was carried out by subjecting the diaphragm assembly to post-deposition heat treatment.

The output characteristics of the transducer were studied using a dead weight pressure calibrator (Model 5020 of Desgranges et Huot, France). The details of the procedure followed are given elsewhere [23].

III. RESULTS AND DISCUSSION

A. Effects of Post-Deposition Heat Treatment on the Thin-Film Strain Gauge System

As can be seen in Table I, the post-deposition heat treatment resulted in a decrease in gauge resistance. The reduction in gauge resistance is attributed to annealing of defects incorporated in the film structure during deposition [24], [25]. It is important to note here that whereas the manganese film pressure transducer [23] had an average reduction of 6.5% in gauge resistance after heat treatment at 120°C, the average reduction achieved in the present Au-Ni film resistance was only 9.29%. Therefore, in order to make sure of the almost complete annealing of defects, the heat treatment process was repeated at 170°C. After the second heat treatment, the average decrease in gauge resistance was 1.36%. However, further heat treatment did not result in any additional decrease in gauge resistance.
The output performance of a thin-film pressure transducer with Au-Ni film as the strain gauge has been studied with continuous excitation for at least 2 h before taking any output readings. It was found that the optimum bridge excitation was 3 V dc, since higher excitation voltages showed instability above 1% FSO which is thought to be due to excessive self-heating. The maximum non-linearity and hysteresis observed after 1000 repeated pressure cycles over a period of 8 months was 0.06% FSO. The output behavior of the pressure transducer with temperature was also studied after stabilizing at each temperature for 2 h and it was found that the net output was linear with a maximum deviation of less than 0.6%.

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References
K. Rajanna graduated from the University of Mysore, India, with the B.Sc. degree in physics and mathematics in 1973. He received the M.Sc. degree in physics from the same university in 1976, and was awarded the M.Sc. (Engg.) degree from the Indian Institute of Science, Bangalore, India in 1988 for his research work on thin-film strain gauges. He started his career in the National Aeronautical Laboratory and later spent some time in the Reactor Research Centre (Department of Atomic Energy), Kalpakkam, before joining the Indian Institute of Science in 1983. At present, he is a Senior Scientific Officer in the Instrumentation and Services Unit of the Indian Institute of Science. His current interest is in the area of thin-film transducers. Presently he is completing the requirements for the Ph.D. degree.

S. Mohan received the M.Sc. degree in physics from Sri Venkateswara University in 1967 and continued to work for the Ph.D. degree at the same university in the field of thin films. He was a member of the teaching faculty of the Physics Department at the Sri Venkateswara University during the period 1970-1977. He was selected as a National Associate under the University Grants Commission in 1977 and worked for 3 months in the Thin Film Laboratory of the Indian Institute of Technology, New Delhi. He joined the Department of Physics, Bangalore, in 1977 as a Senior Scientific Officer and since 1988 has been an Associate Professor in the Instrumentation and Services Unit, in charge of the Vacuum and Thin Films group. In 1981 he was honored by Andhra Pradesh Academy of Sciences with a Young Scientist award. He was awarded the MRSI medal for 1992 by the Materials Research Society of India. His areas of interest include thin-film sensors, superconducting films, optical devices, and tribological coatings. He was the General Secretary of the Instrument Society of India during 1983-1989 and since 1989 has been the Convenor, Thin Films group of the Materials Research Society of India. He has been the Editor of Journal of Instrument Society of India since 1991. He was a Visiting Professor for 3 months in 1990 at Forschung Zentrum, Julich, Germany. He has visited a number of countries to give lectures in reputed laboratories. He has published about 80 scientific publications in refereed journals and 6 review articles.

M. M. Nayak received the B.E. degree in electrical engineering from Bangalore University, Bangalore, India, in 1982. Subsequently in 1984 he received the D.I.I.Sc. degree (a specialized postgraduate diploma in electronics design technology) from the Indian Institute of Science, Bangalore. He has undergone a one-year advanced training program at S.E.P. (Societe Europeenne de Propulsion), France, on space-qualified high-precision pressure transducers. In 1982 he was honored with an NRDC (National Research and Development Corporation of India) award for his developmental work on semiconductor pressure transducers. At present he is an engineer in charge of the developmental cell at the pressure transducer and fabrication facility, LPSC, of the Indian Space Research Organization. He is extensively involved in the development of thin-film technologies for space applications which include pressure transducers, liquid level sensors and cryogenic sensors. He is working towards the Ph.D. degree.

N. Gunasekaran received the degree in mechanical engineering from Madras University, Madras, India, in 1964. He has been with the Liquid Propulsion Systems Centre (LPSC) of ISRO for the last twenty years. He heads various groups engaged in the fabrication of hardware for rocket engines, liquid engines, development and batch production of transducers. At present he is the general manager of the Transducers and Light Alloy Fabrication Centre, LPSC. In recognition of his developmental work on semiconductor pressure transducers, he was honored with an NRDC award in 1982. His areas of interest include the design, development, and fabrication of various components for space application and precision transducers. Recently, he has also been involved in the design and development of cryogenic stages for GSLV (Geo-Stationary Launch Vehicles).

A. E. Muthunayagam was born in India on January 11, 1939. He received the B.E. degree in mechanical engineering in 1960 from the University of Madras, Madras, India, and the M. E. degree in power engineering from the Indian Institute of Technology, Bombay, India, in 1965. He received the Ph.D. degree from the School of Mechanical Engineering, Purdue University, West Lafayette, IN.

He joined the Indian Space Research Organization (ISRO) in 1966. As an outstanding propulsion engineer, he contributed significantly to the rocket propulsion technology development at ISRO. He is primarily responsible for the setting up of the Liquid Propulsion Systems Centre (LPSC) and streamlining its operation in building extensive test facilities for qualifying the space propulsion systems. His achievements also include development of second and fourth liquid stages for the PSLV, reaction control systems, and SITVC for launch vehicle projects such as SLV3, ASLV, and PSLV, monopropellant reaction systems for IRS satellites, and liquid propulsion systems for INSAT-II project. He is the recipient of the Dr. V. M. Ghate Award for the year 1989 from the Aeronautical Society of India. He is involved as a member of several Indian space programme projects/boards. He is also a member of the Space Propulsion Committee of the International Astronautical Federation, Paris, France. He is the Director, Liquid Propulsion Systems Centre (LPSC), ISRO and is also a member of ISRO Council.