Design of a Pressure Display Interface System for MEMS Type Piezoresistive Pressure Sensors

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Abstract: Foot plantar pressure measurement systems form an important class of pressure sensing systems which are popularly used in biomedical applications. Such pressure measurement systems generally have a number of sensors embedded in the plantar base or sole. Sensors could be working on the basis of different sensing mechanisms, among which piezoresistive sensing is considered to give optimum sensitivity, linearity & hysteresis. Piezoresistive sensors are generally based on Wheatstone bridge configuration which gives an advantage of eliminating the effect of temperature coefficient of resistance. This paper proposes a signal conditioning and digitization circuit for a single quarter Wheatstone bridge (WSB) built using strain gauge as well as for a group of six of them as a model for developing circuitry for foot plantar pressure measurement system. Trimming of sensor offset (around 1V) was done using potentiometer. Amplification was done using OP-AMP LF356 which provided a gain of 666, while Arduino Uno was used for Analog-to-digital signal conversion. The digitized data obtained was plotted using a program in MATLAB software. This circuit design was employed to obtain real time pressure plot of polyimide substrate based piezoresistive microcrystalline silicon pressure sensor with additional use of HX711 for signal conditioning. Signal conditioning involves techniques used to enhance the quality of the sensors output signals. The polyimide-based sensor was fabricated using hot-wire chemical vapor deposition (HWCVD) and patterned using photolithography on MJB SUSS4. The sensing material used here was aluminum induced crystallized silicon (AIC-Si) and the sensitivity of this sensor obtained was 77 mV/V/MPa.

Index Terms - MEMS Piezoresistive Sensor, AIC-Silicon, Pressure sensor, Wheatstone bridge, Arduino Uno, MATLAB

I. INTRODUCTION

Micro-electromechanical systems (MEMS) is a process technology which is used to create very small mechanical components which can be integrated with the electrical system and embedded in a single device. The size of MEMS device ranges from a few micrometers to millimeters. These devices are particularly used for sensing and controlling application at micron levels. Generally, MEMS devices consist of sensor & actuator which are embedded on the same chip. Initially MEMS followed the techniques of Integrated Circuit fabrication but with the passage of time, it has developed its own technology in the form of surface micromachining and bulk micromachining [1]. The MEMS pressure sensors can be classified on the basis of the type of energy which gets sensed. It could be one among the following - mechanical, thermal, chemical, radiant, magnetic, or electrical energy.

In the present project, we are focusing on mechanical energy domain, using which force sensors or pressure sensors are generally built. Pressure sensors have widespread applications in several fields such as biomedical, aerospace, automobile, defense etc. [2]. They can be classified on the basis of different sensing mechanisms as follows – Piezoresistive sensors, Piezoelectric sensors, Capacitive sensors. Among these, piezoresistive mechanism is preferred because it allows easy signal processing and usually provides linear operation over a wide range. Also, when one moves from single device to a group of devices used for applications such as foot plantar pressure measurements systems, it is important to inhibit cross talk between sensors for which piezoresistive mode is preferred [3]. Foot plantar pressure measurement systems form an important class of pressure sensing systems due to their established use in diagnosing lower limb problems, footwear design, sport biomechanics, injury prevention [4] as well as for detecting specific medical conditions such as diabetic neuropathy. For instance, regular inspection of foot plantar pressure is considered effective in avoiding diabetic foot ulceration in almost 75% of cases [5].

A pressure sensor typically acts as transducer that transforms the pressure into an electrical signal. Strain gauges generally experience less than 1% change in resistance over their complete range of operation. Hence, it is critical to measure small resistances to get accurate pressure readings. One way to do this is by providing a constant input current and measure the output voltage across the sensor, with both current and voltage readings being accurate. Alternatively, one can use bridge circuits which offer an enhanced output voltage due to possibility of having a single or all active resistors in the bridge. After obtaining the output voltage, the signal undergoes conditioning processes which may include amplification, noise cancellation, filtering etc. Further to this, the analogue to digital processing of the signal is done. Successful application of the device can be established using parameters such as offset, gain, linearity, sensitivity, voltage and current levels, stray impedance, time constants, etc. depending on the application for which the device is being used. In this paper, we have presented circuitry for signal conditioning and digitization which could be used for a single quarter Wheatstone bridge (WSB) sensor, and further for a group of six sensors made using strain gauges. This would be serving as a model for further work on foot plantar pressure measurement system. Also, we demonstrate the use of HX711 for signal conditioning and digitization of a thin film sensor piezo-resistor (micron-sized) fabricated using photolithography and hotwire chemical vapor deposition.

II. WHEAT-STONE BRIDGE CONFIGURATION

Wheatstone bridge configuration is one of the most widely used configurations for piezoresistive pressure sensor applications. During application of pressure, resistance of one or more piezo-resistors change which unbalances the bridge. The change is measured in the form of output voltage which provides an indirect measure of pressure applied. Since, the change of resistances is very small (typically less than 1% of the nominal resistance), hence even an excitation voltage of around 10 V may only produce an output voltage of around tens of millivolts. Wheatstone bridge configuration could be used with single varying element (quarter Wheatstone bridge), with two varying elements (half Wheatstone bridge), or even with all four varying elements (full Wheatstone bridge). Three configurations are shown in Fig.1 [6] along with output voltage and linearity error which occurs in each of them. It is clear that the output voltage increases as one goes from a single varying resistor towards a greater number of varying resistors, as well the linearity error can be nullified by increasing the number of varying resistors.

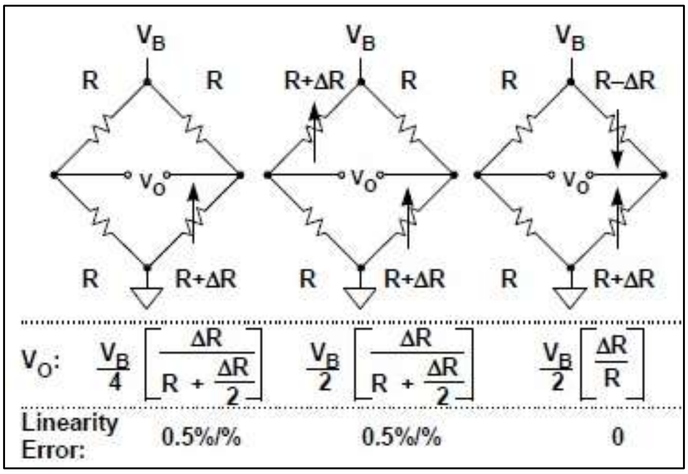


Figure 1. From left, quarter WSB with single resistance increasing, half WSB with both resistances increasing, half WSB with one increasing and other decreasing resistance [6]

In a full Wheatstone bridge circuit with four active resistors, two opposite resistors experience a rise in resistance (R_1 and R_4) while the other two (R_2 and R_3) experience a dip in resistance as shown in Fig. 2. In this configuration, linearity error is zero, sensitivity is highest and thermal effects are greatly minimized. If V_B is the applied bias voltage then output voltage V_O is given by Equation 1. In Equation 1, the quantity GF (Gauge Factor) of the material can be defined as the relative change of resistance per unit strain (ε) experienced by the given piezoresistive material.

$$V_O = \left(\frac{R_3 + \Delta R_3}{(R_1 + \Delta R_1) + (R_3 + \Delta R_3)} - \frac{R_4 + \Delta R_4}{(R_2 + \Delta R_2) + (R_4 + \Delta R_4)}\right) * V_B$$

$$Vo = \left(\frac{(R_2 + \Delta R_2) - (R_1 + \Delta R_1)}{(R_1 + \Delta R_1) + (R_2 + \Delta R_2)}\right) * V_B$$

$$Vo = \left(\frac{2\Delta R}{2R}\right) * V_B = \left(\frac{\Delta R}{R}\right) V_B = V_B * GF * \varepsilon \qquad (1)$$

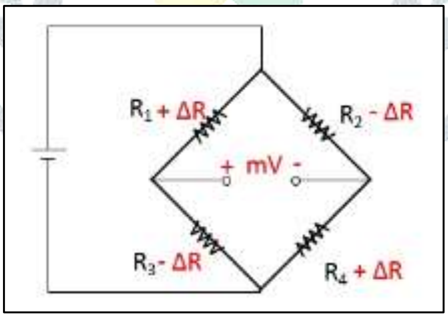


Figure 2. Pressure application on sensor and full wheat-stone bridge circuit

III. SENSOR DESIGN

Full Wheatstone bridge configuration was chosen for the device due to its obvious advantages as described in Section II. The device design was selected after performing simulations in MATLAB [7]. For application of a normal pressure of 100 kPa on a square diaphragm from top, the deflection profile obtained in MATLAB showed that piezo-resistors lying in the central area would have a compressive stress while those at the edges will have a tensile stress (Fig. 3(a)). Hence, the two resistors at the center of device undergo a dip in resistance while the other two at edges experience a rise in resistance. The piezoresistive material chosen was Aluminum induced crystallized silicon (AIC-Si), which is a low-cost high gauge factor material with a reported gauge factor of 43 [8]. By employing photolithography, resistor dimensions as low as 50µm have been achieved as shown in Figure 3(d). Photolithography was carried out in two steps wherein the first step was employed to produce patterned sensing material (Photolithography mask shown in Figure 3(b)) and the second step was for depositing interconnects of Aluminum (Photolithography mask shown in Figure 3(c)). The diaphragm of the device below it is a square of side length 3 mm while the device is in shape of a square of side length 1cm. When stress is supplied normally from the top, the device bends into the diaphragm and experiences a change of resistance as expected.

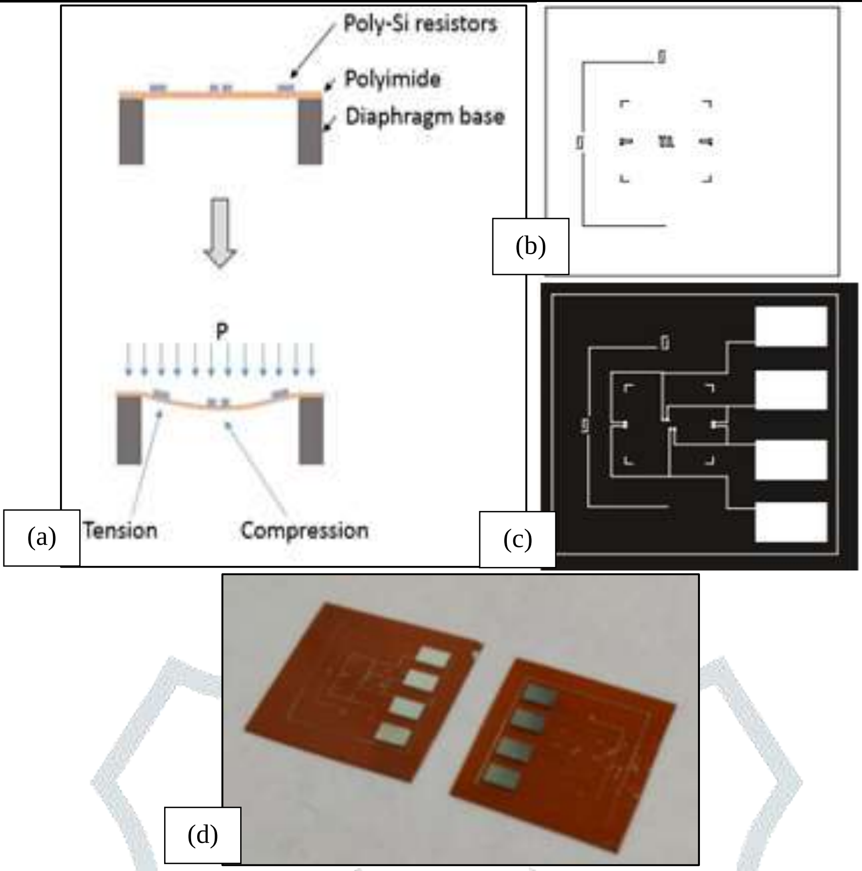


Figure 3(a). Device undergoing compression and tensile stress in different regions (b)Photolithography masks used for depositing sensing material and (c) Aluminum interconnects (d) Devices fabricated by photolithography

IV. SIGNAL CONDITIONING CIRCUITS - HARDWARE & SOFTWARE IMPLEMENTATION

In this section, tools and methods adopted for signal conditioning and digitization for both quarter and full Wheatstone bridge circuits are explained.

4.1 For quarter Wheatstone bridge circuits

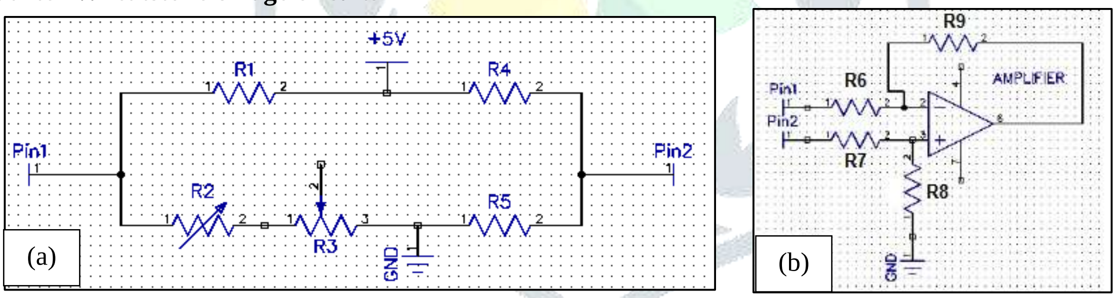


Figure 4(a). Quarter Wheatstone bridge conditioning circuit (b). Quarter Wheatstone bridge signal amplification circuit

Signal conditioning circuits were made and tested for several Wheatstone bridge configurations starting with quarter Wheatstone bridge configuration to full Wheatstone bridge configuration. Initial testing of conditioning circuit was done in quarter Wheatstone bridge using standard strain gauges purchased from market which are basically piezo-resistors. The material used in it is Constantan and has a Gauge Factor of 2.1. The resistance of strain gauge used was 350 ohms and it is connected in series with the trimmer which was used in order to eliminate the offset by balancing the bridge. In order to complete the bridge three 470 ohms resistors were taken as shown in Fig. 4(a). At one of the opposite ends Wheatstone bridge was excited with 5V DC supply and the output was taken from the other opposite end as shown in Fig. 4(a). The maximum output voltage change of the Wheatstone bridge was 4 mV which is not in the range of A/D convertor. Hence, the signal amplification was done using OP-AMP LF356. The resistors used in series with the inverting and the non-inverting terminal were 330 ohms and the resistor used for feedback was 220 kilo ohms as shown in Fig. 4(b). Input supply voltage given to the pin 7 was +15 volts and the voltage given to the pin 4 was -15 volts. Pin 1 and Pin 2 of the Wheatstone bridge was connected to the pin 2 and pin 3 of the differential amplifier. Gain of the amplifier was R_8/R_6 = 220kΩ /330 Ω = 666. Due to high gain, the output obtained from the differential amplifier was more than 2V. The PCB (printed circuit board) for signal conditioning circuit was designed using Dip-trace and imprinted on the circuit board.

Further output of the signal conditioning circuit given to the Arduino board for processing the signal. Arduino Uno was used to carry out A/D conversion (Fig. 5(a)). Arduino circuitry is connected to the USB port of a computer trough the USB cable. The USB connection also facilitates the Arduino to be programmed by the user. Arduino is programmed externally using the Arduino IDE (Integrated Development Environment). The output from the positive terminal of the piezoresistive sensor is fed to Analog Input pin 1 of the Arduino Uno through OP-AMP & other Sensor outputs to the successive Analog Pins of Arduino Uno. The device operates between 1.8 - 5.5 Volts. It has 14 Digital input/output pins as shown in Fig. 5 (a) with analog inputs, a 16 MHz ceramic resonator a USB connection, a power jack, an ICSP header and a reset button. The Arduino Uno can be powered via the USB connection or with an External power supply. Arduino Uno can detect and measure analog values from 0 to 1023. Representative pressure can be visualized by serial monitor platform of the Arduino. After that we build MATLAB model to link serial interface to store real time data generated by multiple sensors for further analysis to the researcher or Data analyst. The working of Arduino based smart pressure sensor algorithm consisted of the following steps:

- Power ON the system which includes the microcontroller, sensors and other peripherals.
- Initialize the system which consist of sensors and user interface. MATLAB code is responsible for analogue data acquisition and storage thereof in a remote database or Computer.
- Read data from the sensors and analyze data to check whether it is required to alert the user or continue monitoring.

In order to place the strain gauge, cantilevers made of mild steel were prepared using laser cutting tool as shown in Figure 5(b). They were placed on the wooden base and polished using 100 grade polishing paper. Then the surface was cleaned with sand paper and acetone. Strain gauges were placed on the end using CN adhesive and then covered with cello tape. Contact leads were soldered with the connecting wires. Signal conditioning circuits were designed using dip trace and later this design was imprinted on the circuit board. All the components were placed on the printed circuit board and interconnects were imprinted on the other side. All the components were soldered on the other side of the circuit board as shown in Figure 5(c).

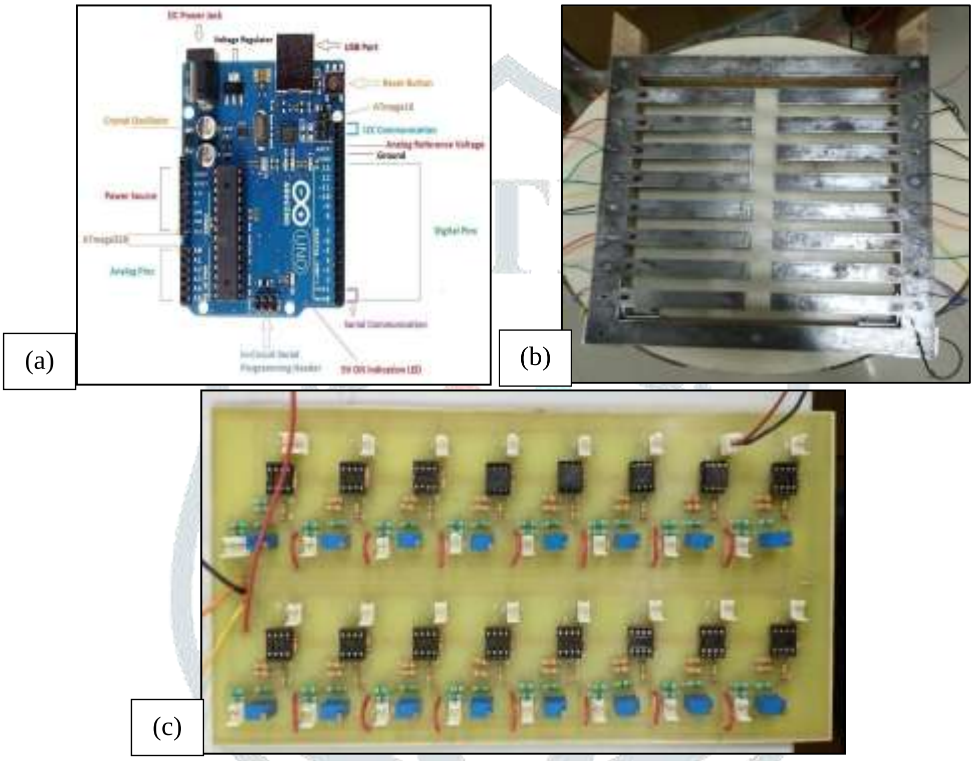


Figure. 5 (a). Arduino Uno (b). Cantilevers made of mild steel used for strain gauge placement (c). Signal conditioning circuit designed using dip trace

4.2 For full Wheatstone bridge circuit in the fabricated device

For full Wheatstone bridge configuration-based device fabricated using AIC-Si as the sensing material. For realization of diaphragm, the base of sensor is made of acrylic material due to its availability, ease of machining and favorable mechanical properties (can hold up to 60-80 MPa). Signal conditioning was done using HX711. This is because the output voltage for the device was measured in millivolts. Basically, HX711 is 24-Bit analog to digital converter (ADC) used for weigh scale application and its peripheral components like capacitor & resistors act a low pass filter which used to allow the low-frequency signal from the sensor to pass while rejecting the high frequency noise. It is an analog-to-digital converter made specifically for weighing scales as well as industrial control application to interface directly with a bridge sensor. It has a resolution of 0.298 μV which makes it ideal for low pressure sensing. Powering & data acquisition was done using Arduino Microcontroller boards. Their connection is shown in Fig. 6. The HX711 communicates to microcontrollers using synchronous serial communication. The HX711 library has been used acquired through Sketch > Include Library > Manage Libraries in the Arduino IDE. It prints the digitized output from the sensor to the serial monitor.

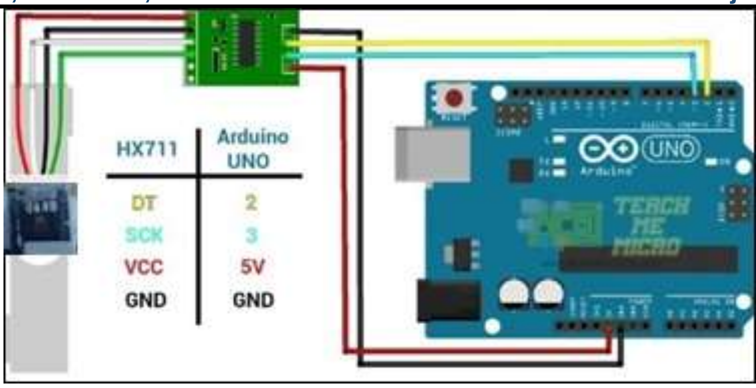


Figure 6. Connection between Arduino, HX711 and device [9]

V. RESULTS AND DISCUSSION

5.1 For a single quarter Wheatstone bridge

At one of the opposite ends Wheatstone bridge was excited with 5V DC supply and the output was taken from the other set of opposite ends. The offset voltage in unstressed condition was found to be 0.9V as shown in Fig. 7(a). This offset was trimmed using potentiometer in the circuit. Then the voltage amplification was done using amplifier and voltage increased to 2.1V in unstressed condition. After applying normal stress to the cantilever caused by its downward bending, amplified voltage increased from 2.1V to 2.7V as shown in Fig. 7(b) thereby increasing the output from 4mV (without amplifier circuit) to 600 mV (with amplifier circuit).

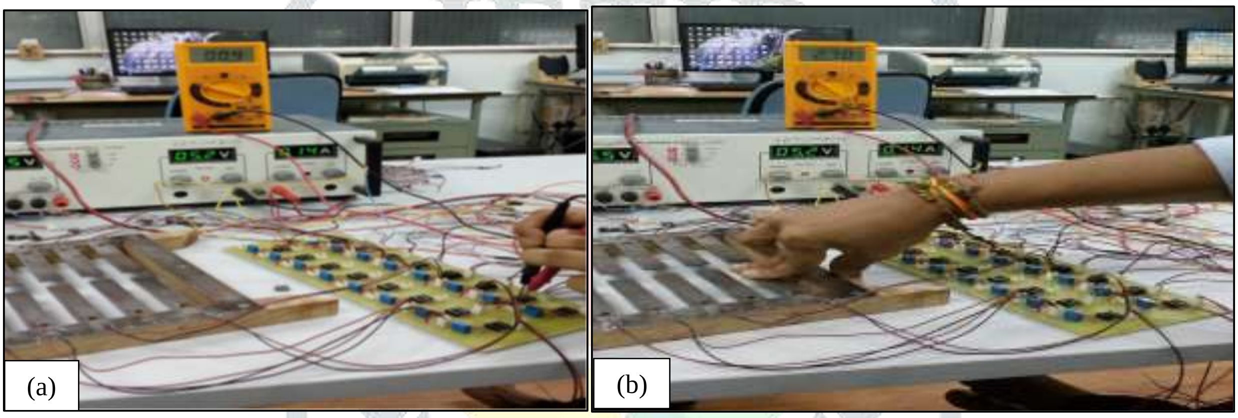


Figure 7(a) Offset voltage from an unstressed single quarter WSB (b) Output voltage after trimming and amplification in stressed condition

5.2 For a group of six quarter Wheatstone bridge circuits

Similar as the single quarter Wheatstone bridge, a group of six similar sensor circuits were supplied with +5V DC supply, and then output was taken after signal conditioning and digitization. This output in Volts was converted to pressure values in kPa by performing calibration using a standard load. The corresponding output in kPa is shown in Table 1. Outputs from the six bridges was displayed graphically using Arduino Uno, as shown in Fig. 8(a). Real time changes while pressing the cantilever for each of the 6 strain gauges could be observed could be seen in the graph representing the change in pressure experienced. For two of the strain gauges, the sensor output is represented as a 3D graph through a program in MATLAB, as shown in Fig. 8(b).

Table 1. Output from six strain gauges expressed in kPa (recorded on 30th April, 2021)

Sensor_1	Sensor_2	Sensor_3	Sensor_4	Sensor_5	Sensor_6
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.90029	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.602151	1.368524	0.684262
73.80254	58.35777	24.63343	8.406647	1.368524	0.684262

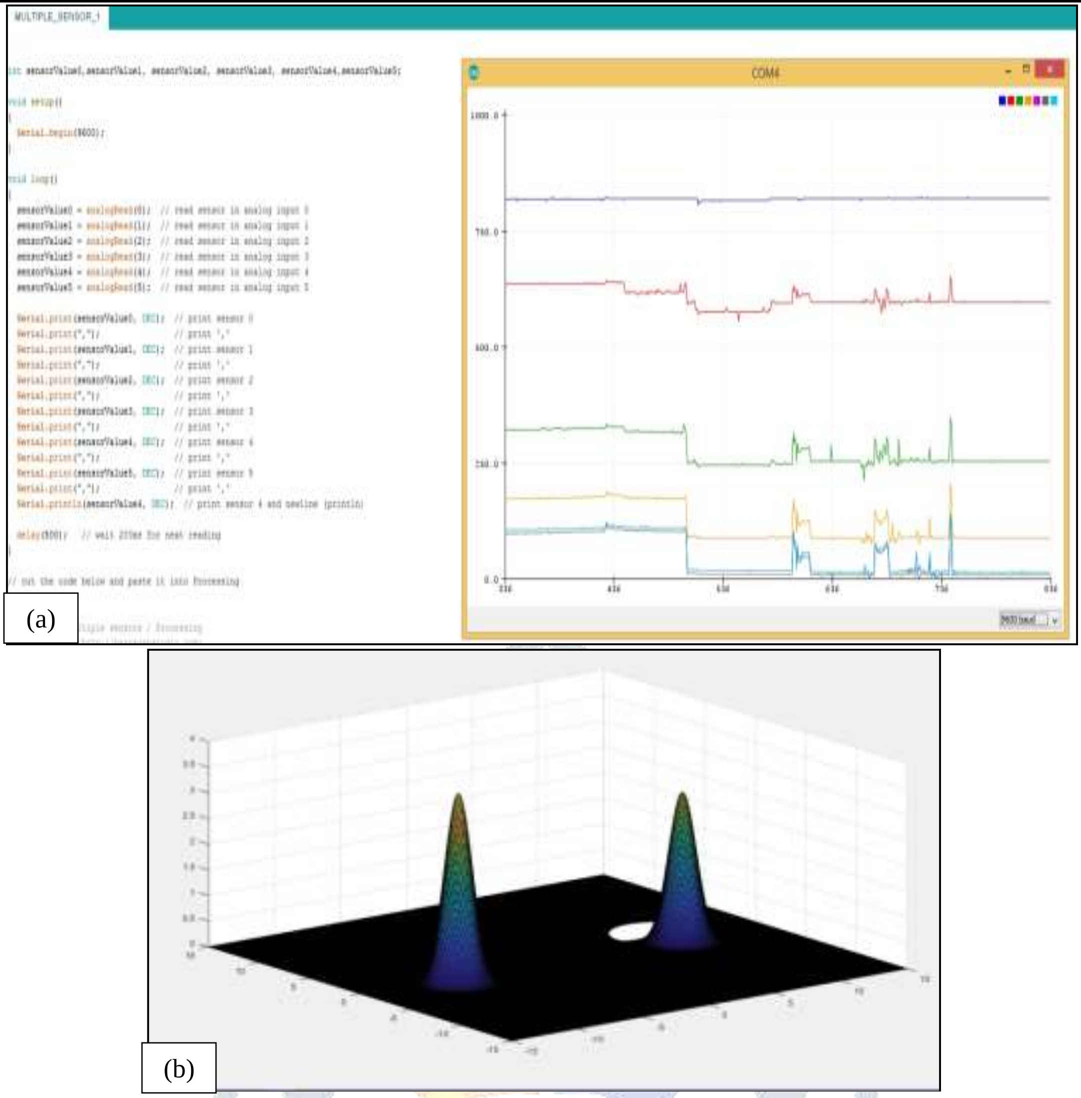
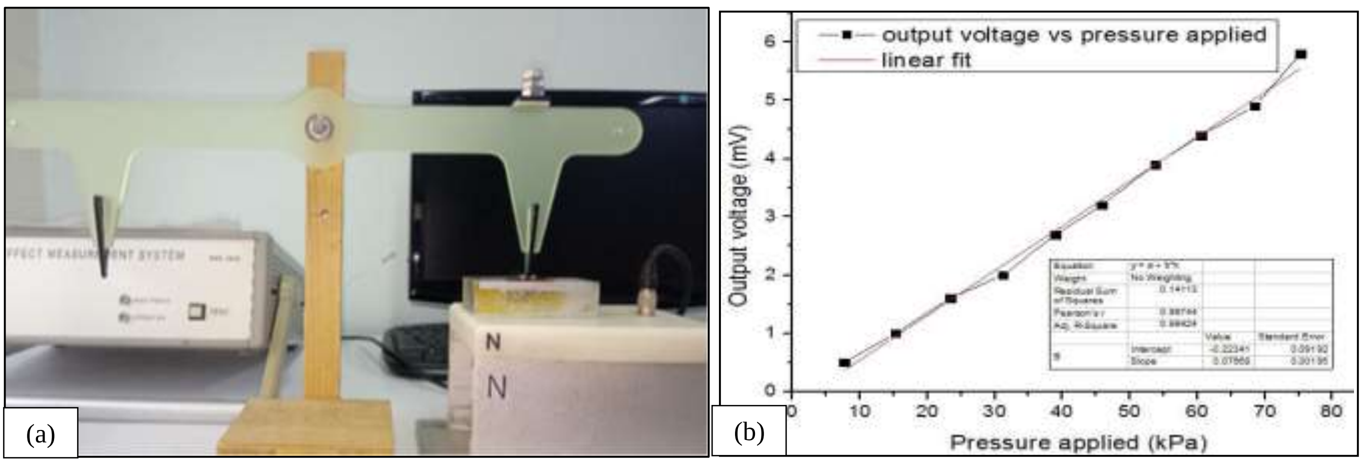


Figure 8(a) Real time output from six sensors displayed using Arduino (b) Mapping of Two Sensor using MATLAB

5.3 For the fabricated device with full Wheatstone bridge

For the fabricated device using AIC-Si, initially sensitivity was found in order to gauge the range for full scale reading of the output which is important parameter for conditioning circuit. Sensitivity was found using an in-house pressure application set-up as shown in Fig. 9(a). The sensor device consists of a diaphragm in the center with a piezoresistive element present just over it. Diaphragm deflects due to applied pressure in the range of 1 kPa to 100 kPa and is detected by piezo-resistors. The change in its resistance results in variation in current and voltage across the resistive element. Bias provided to the DUT was 1V. Pressure application was done using nuts (0.5inch size) from 0 to 10 in number, and the pressure applied was calibrated using a standard Honeywell pressure sensor. Sensitivity of the device in loading cycle was found to be 76.6 mV/V/MPa and the response was highly linear with R-sq.% to be 99.4% (Fig. 9 (b)).

For output response with signal conditioning circuit using HX711, connections were made as given in previous section. Circuit connection is shown in Fig. 9 (e). First, the serial monitor values were noted when nothing was on the sensor (Fig.9(c)). Then, sensor was pushed normally using thumb tip for a second and removed. The output signals observed graphically are shown in Fig. 9 (d). Very clear spikes of pressure could be seen in the graph.



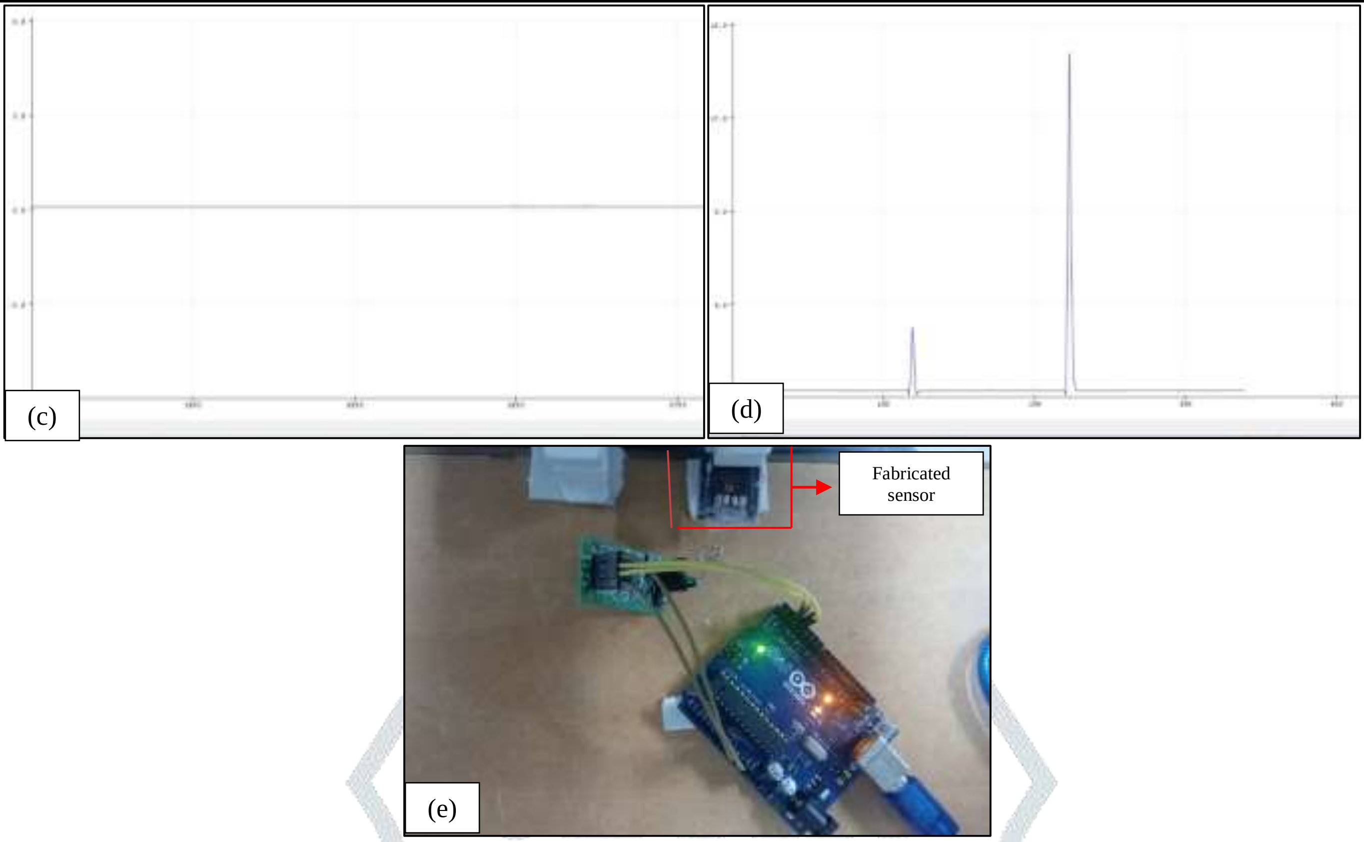


Figure 9 (a) Pressure sensitivity measurement set-up (b) Sensitivity curve for fabricated sensor (c) Serial monitor with no load (d) Serial monitor when sensor pressed at the centre with thumb (e) Circuit connection of sensor with HX711 & Arduino

VI. CONCLUSIONS

The circuitry designed for signal conditioning and data acquisition of quarter Wheatstone bridge, made of strain gauges, has been extended to the polyimide substrate based piezoresistive pressure sensor by additionally employing HX711. Using this same circuit and data acquisition method we have successfully obtained the real time pressure plot for the fabricated pressure sensor having AIC-Si as the sensing material. Arduino based controller has been employed as it is easy in implementation, operation and cost effective. Real time visual plotting has been done using MATLAB tool. In further experiments we will extend this to an array of pressure sensors on a foot plantar pressure measurement system for clinical foot analysis.

VII. ACKNOWLEDGMENT

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VIII. AUTHOR'S CONTRIBUTION

All works with relation to this paper have been accomplished by all the author's efforts. Mr. Sachin performed most of the signal conditioning experiments. MEMS pressure sensor used is proposed & fabricated at Dept. of Metallurgical Engineering & Material's Science, IIT Bombay by a team headed by Prof. (Dr.) Rajiv O. Dusane. The experiments regarding design, fabrication and signal conditioning of fabricated pressure sensor were completed with the help from Mr. Anand Ratna Arun (PhD Research Scholar, IIT Bombay) & Mr. Swapnil Sisle (M. Tech, IIT Bombay). Apart from that Mr. Vedant D. Manjrekar (R & D Engineer) helped us in PCB design, fabrication & testing. Finally, every segment related to this paper is accomplished under the guidance from Prof. Maruti B. Limkar & Prof. (Dr.) Balaji G. Hogade. All the authors reviewed the manuscript.

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