Sensors and Actuators A 280 (2018) 125–131

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Highly sensitive giant magnetoresistance (GMR) based ultra low differential pressure sensor

Umesh P. Borole[a,b], Sasikala Subramaniam[a], Ishan R. Kulkarni[a], P. Saravanan[c], Harish C. Barshilia[a], P. Chowdhury[a,b,*]

[a] Nanomaterials Research Laboratory, Surface Engineering Division, CSIR – National Aerospace Laboratories, Bangalore 560 017, India
[b] Academy of Scientific and Innovative Research (AcSIR), CSIR-NAL Campus, Bangalore 560 017, India
[c] Defence Metallurgical Research Laboratory, Hyderabad 500 058, India

ARTICLE INFO

*Article history:*
Received 2 March 2018
Received in revised form 19 June 2018
Accepted 11 July 2018

*Keywords:*
Pressure sensor
Magnetoresistive sensor
Surface mounted

ABSTRACT

In this study, we demonstrate a simple, cost-effective, giant magnetoresistance (GMR) based magnetic pressure sensor. The basic principle lies behind the measurement of the change in the magnetic field profile generated by the deflected diaphragm attached with a permanent magnet. This magnetic field profile change on the sensor surface was measured by highly sensitive magnetoresistive gradiometer sensor. Based on studied magnetic field distribution of a magnet, a prototype pressure sensor was designed and fabricated, which consists of a polymer diaphragm, a permanent magnet and a giant magnetoresistance based magnetic field gradient sensor. The fabricated prototype was calibrated for ultra-low differential pressure range and it shows: (i) sensitivity up to 16.67 μV/V/Pa and (ii) nonlinearity of 1.5% FS in the range of 0–300 Pa. The real time application was demonstrated where, the sensor was flush mounted on a NACA 4415 airfoil, and both the static and the dynamic suction pressures were recorded as a function of the wind velocity and also with different angle of attack (AOA). The measured pressure was found to be highly accurate while compared with existing static measurement system.


## 1. Introduction

With advancement in technology, uses of pressure sensors are becoming prevalent in consumer electronics, medical, industrial, automotive and aerospace applications [1–3]. MEMS based piezoresistive and capacitive pressure sensors are popular because of their fabrication compatibility with CMOS process. Piezoresistive pressure sensors are preferred choice due to their high sensitivity, miniature size and large scale fabrication. The large temperature dependence of piezoresistive coefficients can be suppressed by the temperature compensation circuits [4]. Though the power consumption in piezoresistive sensor is high, they the are first choice for applications involving high accuracy and sensitivity. Capacitive pressure sensors based on displacement measurement of diaphragm are less sensitive to such temperature drifts, consume less power but often exhibit higher nonlinearity and low SNR due to small capacitance values [5–7]. Other displacement based pressure sensing principles include magnetic and electromagnetic principles. Electromagnetic pressure sensors are based on the concept of inductance, reluctance or Linear Variable Differential Transformer (LVDT) principles. Whereas magnetic pressure sensors use Hall or magnetoresistance based solid state magnetic sensor and a permanent magnet [8–11]. Yu et al. have reported the Hall based pressure sensor, where the thin Hall element formed on silicon membrane acts as diaphragm [8] and a permanent magnet is used as the source of the field. In the pressure range of 300–1100 Pa, they have achieved the sensitivity of the order 0.03 mV/Pa with a excitation current of 50 mA. To the best of our knowledge there is no report on the development of pressure sensor based on magnetoresistive technology.

Several applications demand a measurement of ultra-low differential pressure, for example, HVAC and pneumatic control in industries, air flow monitors, respiratory machines in medical. Aforesaid pressure sensors are successfully implemented for measurement of the pressure in low, medium and high range. When ultra-low differential pressure range (0–10 kPa) is considered, it becomes difficult to achieve high sensitivity with good linearity. A trade-off between sensitivity and linearity is observed in designing of pressure sensor in this range. Higher sensitivity can be attained by increasing the size or by reducing the thickness of the diaphragm. However, it is limited by nonlinearity and low burst

* Corresponding author at: Nanomaterials Research Laboratory, Surface Engineering Division, CSIR – National Aerospace Laboratories, Bangalore 560 017, India.
*E-mail address:* pchowdhury@nal.res.in (P. Chowdhury).

https://doi.org/10.1016/j.sna.2018.07.022
0924-4247/

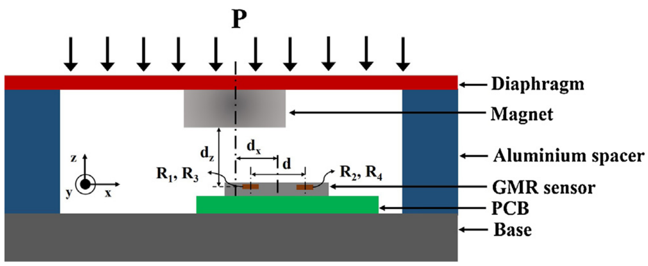


**Fig. 1.** Illustration of magnetic pressure sensing mechanism.

pressure. Nevertheless, the advances in MEMS processing allow fabrication of ultra-low pressure sensors. The complex geometries and number of processes involved increase the end cost of the final product [12–14].

In this report, we propose a magnetic sensor based pressure sensor. The concept of the sensing mechanism lies behind the measurement of the change in the field gradient caused by a movable magnet attached to the diaphragm. In this study, we focused on the design and fabrication of a prototype pressure sensor to measure the differential pressure in ultra-low pressure range. A detailed finite analysis was carried out to operate the pressure sensor in the higher sensitive region. Finally, the fabricated sensor was mounted to measure the ultra-low differential pressure on a surface of airfoil in a wind tunnel and the results were presented.

## 2. Theory of sensing mechanism

The proposed pressure sensing mechanism is illustrated in Fig. 1. The sensor consists of a diaphragm, a rare earth permanent magnet and a giant magneto-resistance (GMR) based magnetic field gradiometer sensor. The deflection of the diaphragm attached with the magnet due to the external pressure causes a change in the magnetic field profile, which was sensed by the magnetic field sensor. In this study, an in-house developed GMR based gradiometer sensor (refer Fig. 2(a)) was used. A fabricated GMR based gradiometer has four identical GMR resistors configured in the form of a Wheatstone bridge such that the pairs of two GMR elements are separated by a center to center distance of $d = 1.25$ mm as shown in Fig. 2(b) and (c). Each resistor has an active area of 300 μm × 250 μm and the bridge resistance was measured as 6.3 ± 0.3 kΩ. GMR characteristic of a typical sensor is shown in Fig. 2(d). The sensor shows 12% change in resistance in field of 0 to ±160 G. The sensitivity of single GMR resistor is 0.06%/G. The hysteresis of 9% FS and non-linearity less than 2% FS were measured between 25 G and 160 G for either polarity (Fig. 2(d) inset). It is to be mentioned that the sensor sensitivity is confined within the *xy* plane and along the *x*-direction (along the length of resistor).

When the magnetic sensor was brought to the close proximity of a magnet separated by the distance $d_z$, with an off-center distance of $d_x$ between the center axis of the magnet and the sensor as shown in Fig. 1, the opposite pairs of resistors were exposed in different magnetic fields. To figure out the exact field values at these resistors locations, Finite Element Method (FEM) analysis was performed. In this calculation, an axially magnetized disc-shaped (Φ3 mm × 1.5 mm) NdFeB magnet with remanent flux density of 1.32 T was used. Fig. 3(a) presents the top view of the *xy* plane in Cartesian co-ordinate system where magnet axis touches the sensor surface referred as the origin, i.e., $x = 0$ and $y = 0$. With respect to this co ordinate system, four GMR resistors in the *xy* plane are located at ($x = 0.38$ mm, $y = \pm 0.29$ mm) and ($x = 1.63$ mm, $y = \pm 0.29$ mm) and the center of the sensor is at ($x = d_x = 1$ mm, $y = 0$).

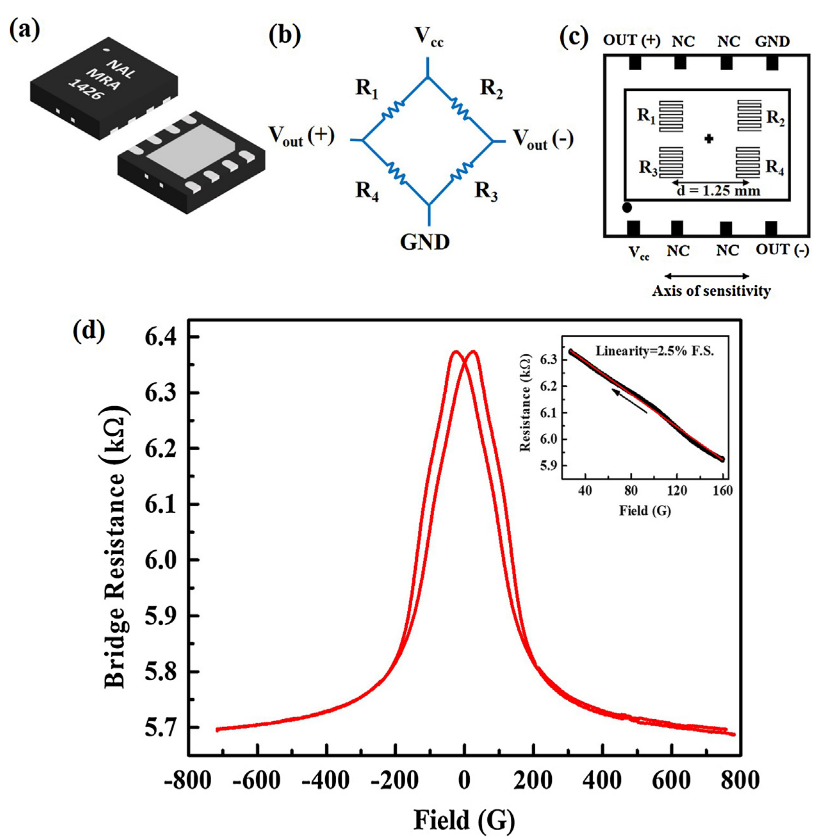


**Fig. 2.** (a) 8 T DFN packaged GMR gradiometer sensor, (b) Wheatstone bridge equivalent circuit of the GMR sensor, (c) configuration of GMR sensing resistors with respect to sensor package, and (d) measured GMR characteristics of a single resistor. The linear region extends from 40 G to 160 G (inset).