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Design and Characterisation of Screen-Printed Piezoresistive Cantilever for Strain Sensor Application

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ABSTRACT

This work addresses the increasing demand for reliable, sustainable and sensitive sensor devices in the sensing field. Conventional methods usually use silicon as substrates and present challenges such as inflexibility and limitations of the substrate that can be used. To overcome this, in this work, a sensitive substrate such as Bristol paper based on screen printed piezoresistive for strain sensor has been designed, fabricated, and tested. A 350 gsm Bristol paper was used as the substrate material, and graphite and silver ink were used as piezoresistive and electrode pad, respectively. The screen-printing method was used to fabricate the strain sensor. The proposed sensor can measure a strain range from 5 mN to 19.6 mN with a force resolution of 196 uN. The implemented sensor has a sensitivity of 0.38 N^{-1}.

1. Introduction

The advent of smart textiles, wearable computing, and intelligent textiles has revolutionised the field of engineering and research. The increasing demand for reliable and sensitive sensor devices has led to the exploration of new materials and fabrication techniques [1,14]. Researchers have used conventional, complementary metal-oxide semiconductor (CMOS) technology for a very long time to fabricate sensor devices using different fabrication technologies such as microelectromechanical systems (MEMS) and low-temperature co-fired circuits (LTCC); this technology is known for its reliability and high performance [1,14]. However, the conventional CMOS methods use silicon as the substrate material of the sensor, which presents significant challenges and limitations. It is inflexible, requiring extensive chemical-mechanical polishing to thin down the substrate to micro thickness before it can be utilised [1]. Sensitive substrates such as paper or fabric are incompatible with the fabrication process. This study aims to investigate and explore screen-printing technology's potential for fabricating sensitive substrates using Bristol paper.

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The simplicity and ease of customization of screen-printing technology make it a promising alternative for producing large quantities of devices, including sensors, capacitors, and inductors [3]. Several studies have reported the successful use of screen-printing technology for the fabrication of piezoresistive [4], capacitive [5], and piezoelectric sensors [6]. Sensitive substrate such as fabric was also demonstrated by using the screen-printing method to fabricate a cantilever [7], beam resonator [8] and diagram structure for a buzzer [9,10].

This research used Bristol paper (350GSM thick) as the substrate and followed a new process to fabricate a piezoresistive sensor device in a flexible way. Graphite material and silver paste were used as the sensing and electrode components, respectively. Both of the components were fabricated using the screen-printing method.

2. Experimental Design

2.1 Working Principle

The working principle of the fabricated sensor device is based on the printed graphite material that works based on the piezoresistive effect. The conventional design of this sensor usually uses a cantilever beam inducing strain and stress [6]. Based on the piezoresistive effect of the graphite material, the strain is converted into a resistance change by the sensing component, which can easily be detected by the designed electrical instrument. Bristol paper 350 gsm thick is used as a substrate material to create the sensor. Screen printed technique is used to apply the graphite material on the fixed end of the cantilever beam that functions as a sensing component. When the force is applied on the free end of the cantilever, the strain on the beam will change sensitively, which will be detected by the piezoresistive sensing component.

Eq. (1) represents the principal operation of the designed sensor where the changing of the sensor resistance,($\frac{\Delta \mathrm{R}}{\mathrm{R}}$), mainly depends on the gauge factor,($\mathrm{G_F}$), of the graphite material, and the strain (e) value induced from the external force applied on the free end of the cantilever [6].

$$\frac{\Delta R}{R} = G_F e \tag{1}$$

2.2 Cantilever Device Structure

The schematic cantilever structure of the Bristol paper-based strain sensor device is shown in Figure 1 and the dimensions of 30 cm in length, 5 cm in width and 0.305 cm in thickness were used. The mechanical properties of the cantilever structure such as the Young's module and the density as shown in Figure 2. According to Eq. (2), Young's module of the Bristol material can be calculated by measuring the deflection of the cantilever under externally applied mass.

In this structure, a piezoresistive material made of graphite is located at the fixed end of the cantilever beam. When an external force is applied on the free end of the cantilever, the sensing material will experience a mechanical strain, which then induces and forces the graphite material's inner structure to change its resistance. Measuring the change in resistance can reflect the magnitude of the induced strain.

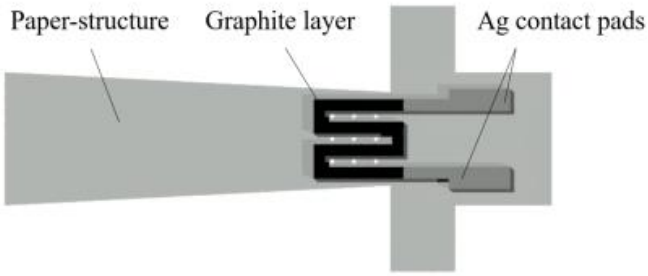

Fig. 1. Schematic structure of a Bristol paper-based strain sensor. Graphite material is used as the sensing component

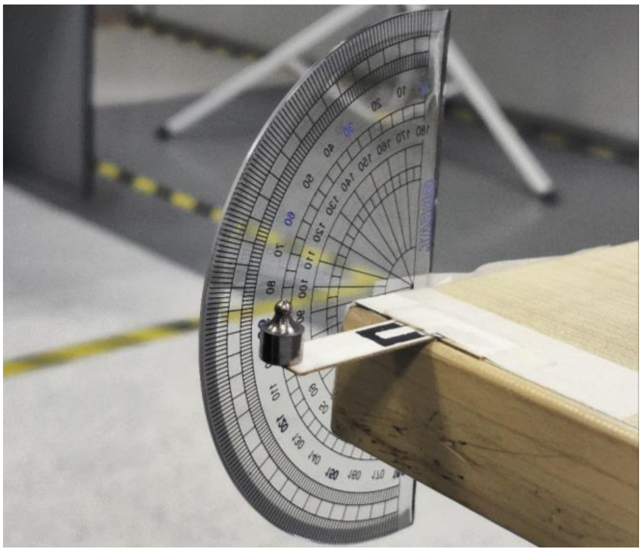

Fig. 2. A photograph of a screen-printed piezoresistive strain sensor

According to Eq. (2), the applied forces on the cantilever's free end are measured as it deflects, enabling the calculation of Young's modulus of the Bristol paper material, where E is the Young's modulus of the Bristol paper, F is the applied force, e is the beam deflection L, W, and H are length, width, and thickness of the Bristol paper cantilever beam, respectively [2].

$$E = \frac{o}{E} = \frac{6\, F_X L}{e\, t^2 w} \tag{2}$$

2.3 Screen-printing Fabrication Process

The fabrication process of the screen-printed Bristol-paper-based strain sensor is shown in Figure 3. A low-power laser machine (Epilog Helix 24, 60W) fabricates the Bristol paper cantilever structure and the stencil mask pattern. Bristol-paper cantilever is designed using the AutoCAD 2022 software and then uploaded into the laser machine to be cut precisely as designed. As illustrated in Figure 3(a), Graphite sensing material and silver ink (SCP) are printed using the stencil mask by following the screen-printed technique, where a squeegee is used to print the material following the designed pattern of the stencil mask as shown Figure3(b), (c) and (d) respectively. The ink or paste is then left to dry for 15 min, and the resistance is measured as explained in the section below.

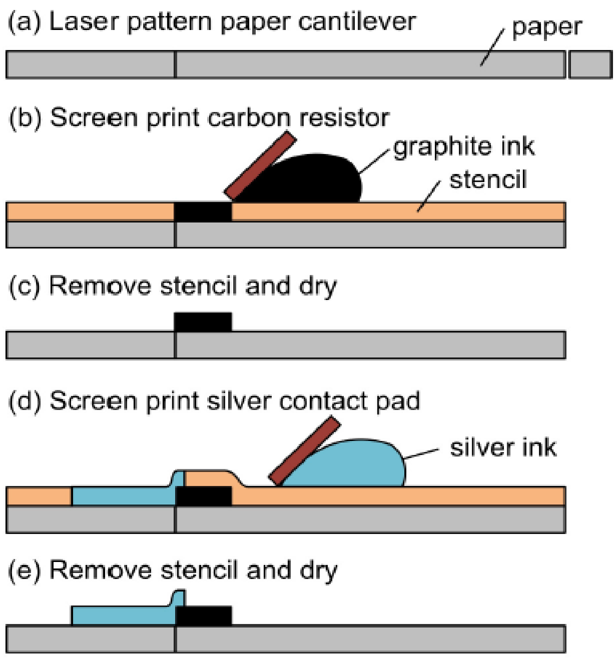

Fig. 3. Fabrication process of the screen-printed piezoresistive strain sensor [8]

2.4 Test Platform

In order to be able to detect the resistance change of the graphite sensing material due to the induced strain of the cantilever structure, a whetstone bridge circuit and an instrumentation amplifier INA128 are successively employed as demonstrated in Figure 4.

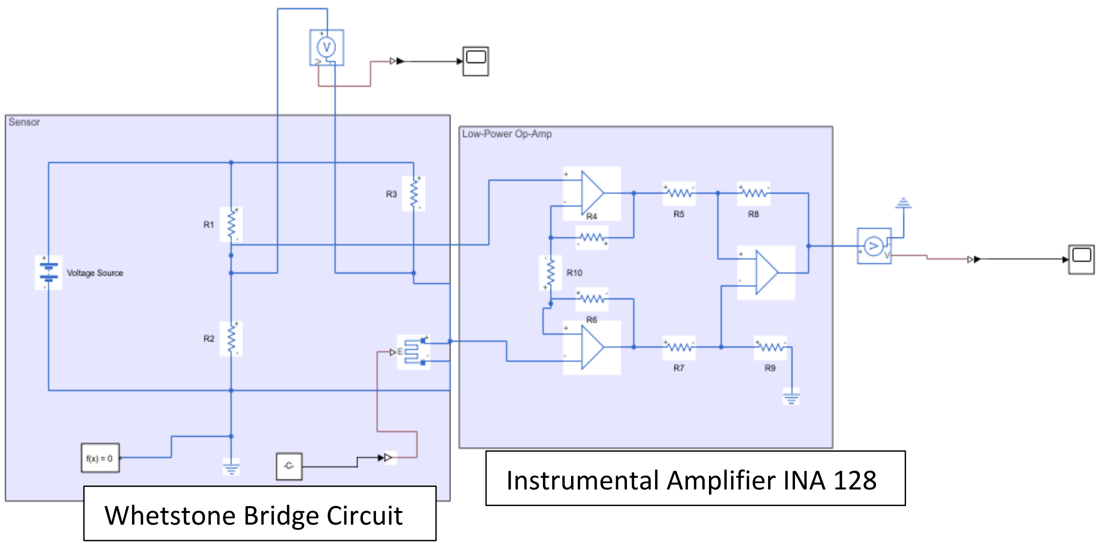

Fig. 4. Schematic of the whetstone bridge circuit with instrumental amplifier INA 128

The main aim of the whetstone bridge circuit is to detect the graphite layer's unknown resistance value and eliminate the sensor's temperature effect [11,12]. At the same time, this circuit calibrated the system output by initially balancing the two legs of the whetstone bridge in order to get a balanced output voltage between the bridge legs. An instrumentation amplifier is used to amplify the differential voltage between the unbalanced bridge in the whetstone bridge by adjusting the gain resistance. The output voltage formed at the output of the instrumentation amplifier, as a result of increased strain in the graphite sensing component, is then amplified via the instrumentation amplifier and fed into the oscilloscope controlled by a personal computer. The complete experiment setup of the tested sensor is shown in Figure 5.

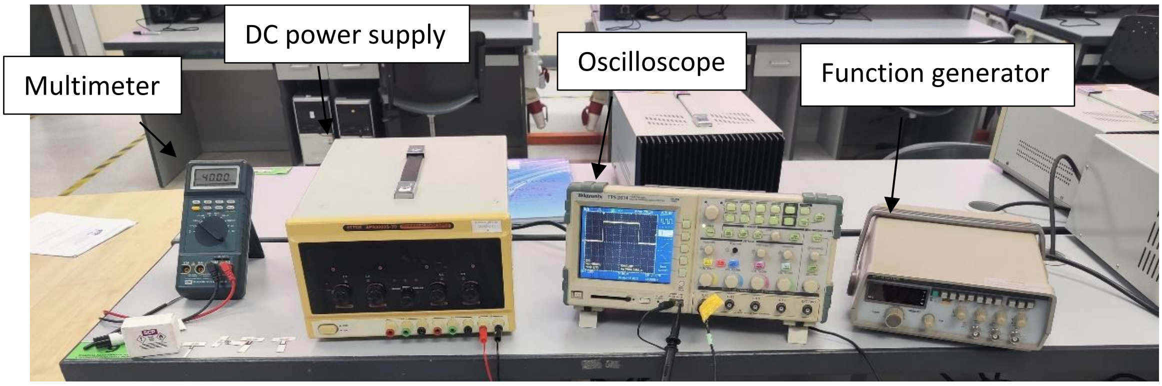

Fig. 5. The test bench of the screen-printed strain sensor

3. Results and Discussion

3.1 Mechanical Properties of the Screen-printed Strain Sensor

Young's module of the cantilever was calculated to be 3.2 GPa using Eq. (2), which is 5000 times lower than Young's module of silicon (usually 150 GPa for crystal silicon) [13]. The range of applied mass on the tip of the cantilever was 0.1 mg to 19.6 mg as shown in Figure 7. According to the graph in Figure 6, there is a linear relationship between the deflection of the cantilever beam and the applied force on the cantilever, where when the applied force increases, the deflection of the sensor's substrate material also increases.

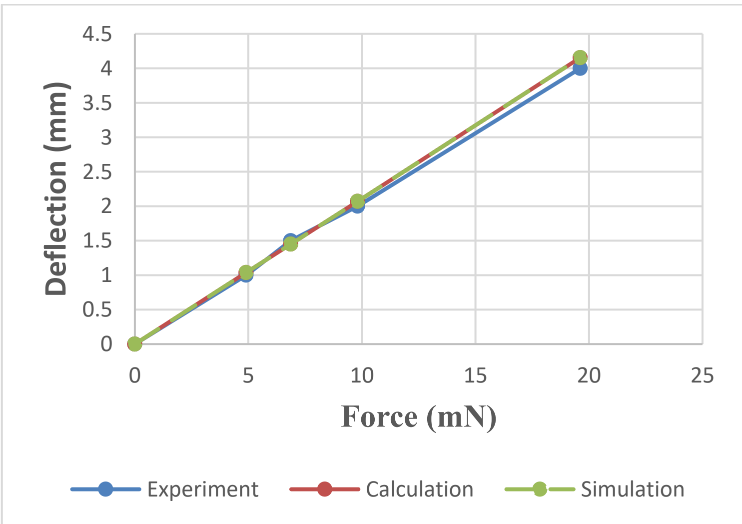

Fig. 6. The mechanical properties of the Bristol-paper cantilever beam

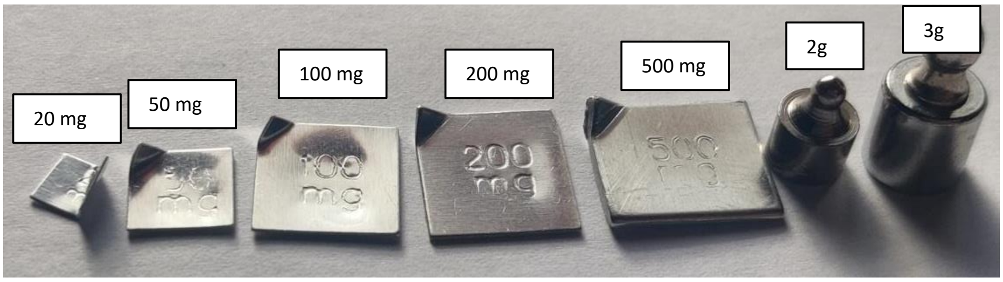

Fig. 7. Weight calibration sample

The strain results of the fabricated sensor have been measured from the experiment and the simulation using COMSOL Multiphysics 5.6v software and the results are shown in Figure 8, respectively.

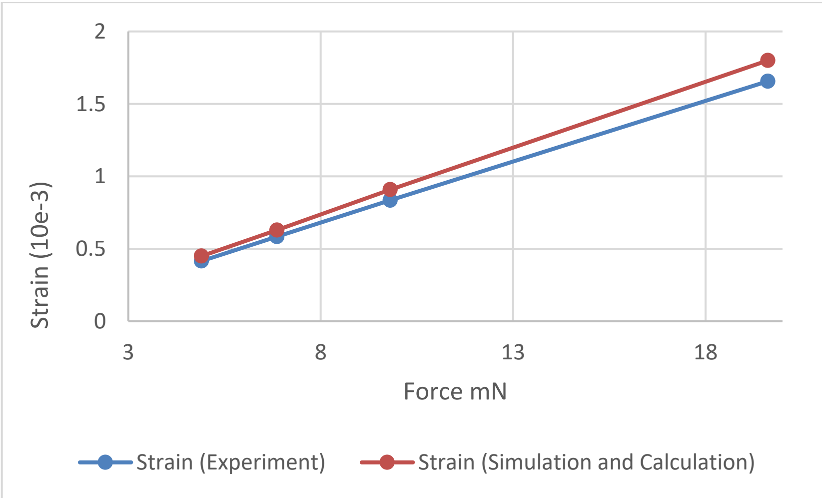

Fig. 8. Experiment and simulation results of the designed sensor

Figure 9 shows that the strain is induced due to the applied external force on the free end of the cantilever, and a maximum strain occurred at the fixed end. Hence, it changes the inner structure of the sensing components, changing the material's resistance. This also affects the sensor's design, where the graphite layer is placed at the maximum strain. The strain can be easily determined by dividing the stress applied to the material by the elastic modulus of the cantilever.

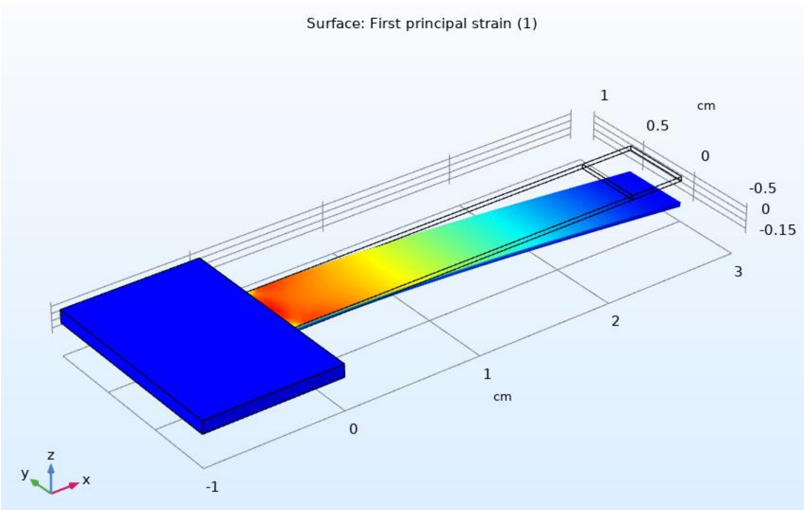

Fig. 9. COMSOL strain simulation of the sensor (0.002 max strain)

3.2 Electrical Properties of the Screen-printed Strain Sensor

The characteristic of the graphite resistors was measured using a digital source meter under ambient conditions of 25 °C temperature and 50% relative humidity. As depicted in Figure 10, the fabricated sensor exhibited an initial measured resistance of 1.113 kΩ prior to the application of any external force. This value also correlates with the value given in the graphite datasheet [3]. This resistance value was determined by the dimensions, specifically the length and width, of the graphite material in the patterned configuration of the graphite ink. The fabricated sensor's resistor showed a linear increase with the increase of applied force between 5 mN to 19.6 mN on the tip of the cantilever beam.

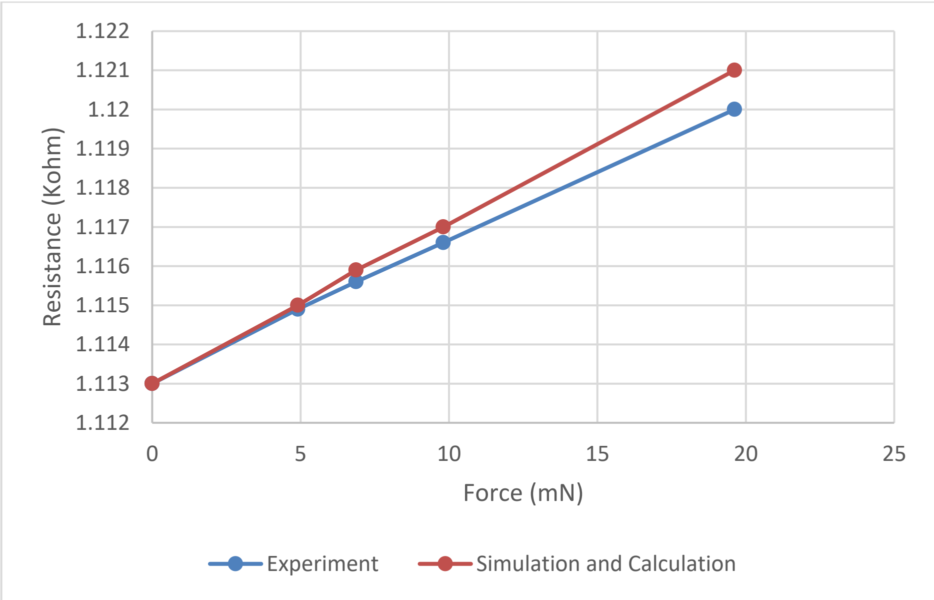

Fig. 10. The resistance changes of the fabricated strain sensor

Figure 11 presents the sensitivity plots depicting the resistance change of the proposed strain sensing system in response to the application of an augmenting point force. This force induces a linear increase in the deflection of the cantilever's free end. As the deflection of the sensor gradually rises from 0 to 4.1mm, a proportional linear increase is observed in the normalised resistance changes (ΔR/R); due to the strain change that occurred on the piezoresistive location which caused the change in sensor resistance. These changes range from 0 to a maximum value of 0.00721 Ω/Ω. It is important to note that this maximum value of 0.00721 Ω/Ω represents the normalised resistance change without any deformation in the sensor structure's substrate material.

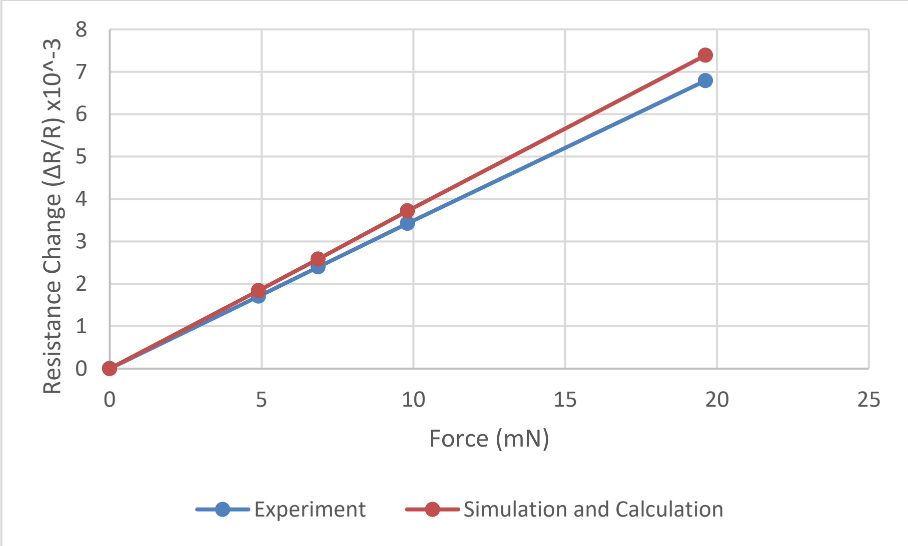

Fig. 11. The test results of the screen-printed strain sensor, relative resistance change against the applied force

Figure 12 shows the electrical properties of the designed strain sensing system versus the force applied to the cantilever structure of the sensor; the sensitivity of the proposed method is computed as voltage change over force in $\mathrm{mV/mN}$. From Figures 10 and Figure 11, the sensitivity of the system under test is calculated as $0.38/\mathrm{N}$ and $8.2\ \mathrm{mV/mN}$, respectively. This result shows that screen printed technology is comparable with other fabrication technologies such as micro-electro-mechanical systems and low-temperature co-fired circuit LTCC. Table 1 represents a comparison between these technologies in terms of sensitivity.

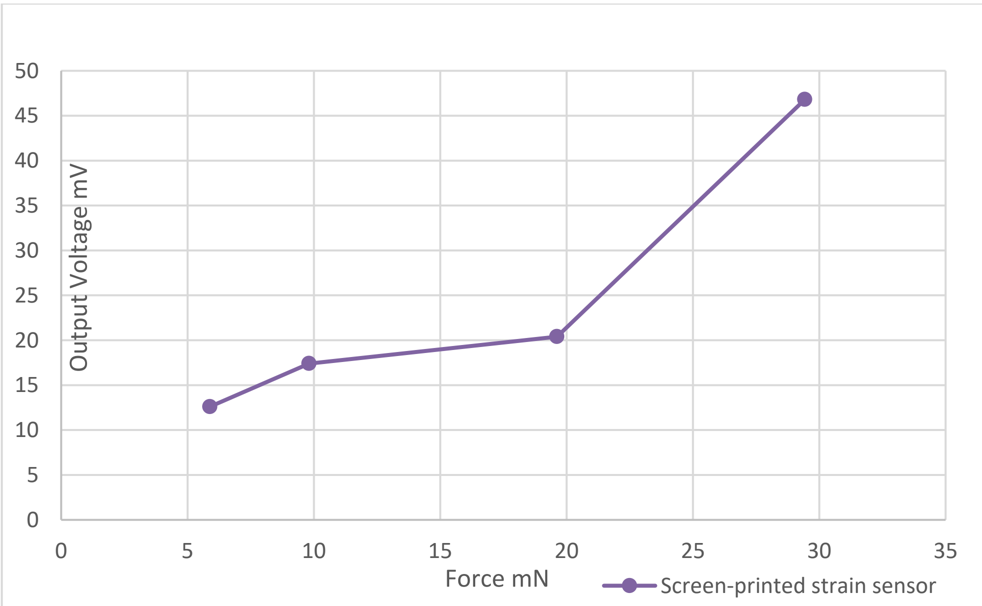

Fig. 12. The output voltage change verses the applied force

Table 1
Technology comparison with existing Piezoresistive based cantilever

Technology	L/w/t (mm/mm/um)	$E\ /G_F$ GPa / -	$S\ (N^{-1})$	Ref
Silicon Si (MEMS)	1/0.35/100	180/50	393598	[14]
SU8 Polymer	0.22/0.28/1.5	4.5/2	931	[15]
LTCC Ceramic	15/3/130	150/10	0.118	[16]
Screen-Printed	30/5/305	3.2 (+-0.05)/4.1	0.38	

4. Conclusions

In this work, a Bristol-paper cantilever based on a screen-printed piezoresistive strain sensor has been designed, fabricated, and tested along with a read-out circuit that consists of a whetstone bridge and instrumentation amplifier. 350 GSM Bristol paper is employed as the substrate material of the sensor cantilever and it is coated with Graphite and silver ink using a screen-printed technique to form a strain sensor. The proposed strain sensor system can measure a strain from the force up to 19.6 mN. The implemented sensor has a sensitivity of 0.38/N which shows a better sensitivity compared to low temperature co-fired circuit fabrication technique as shown in Table 1.

Screen-printed strain sensors offer cost-effective and durable sensing solutions, but further optimisation is necessary to improve sensitivity and linearity for wider applications. Key areas for optimisation include adjusting printing pressure and controlling ink drying conditions to enhance uniformity and reliability. Exploring different ink formulations and substrate materials can also impact sensor performance. A design of experiments approach can systematically analyse the effect of printing parameters, while new techniques like sacrificial screen-printing offer potential improvements. Further research is needed to identify optimal combinations for achieving the best sensor performance.

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