GRAPHITE-ON-PAPER BASED TACTILE SENSORS USING PLASTIC LAMINATING TECHNIQUE

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ABSTRACT

We report for the first time a highly sensitive paper-based tactile sensor using laminated graphite drawn on paper. Thanks to the high gauge factor of 26.2, as well as its excellent robustness and humidity-resistance, plastic-laminated graphite-on-paper has a high potential for mechanical sensors. Additionally, the plastic lamination combined with the laser cutting technique proposed in this study would enable the mass production of cleanroom-free fabrication and low-cost MEMS devices.

INTRODUCTION

In the last two decades, humanoid robots have attracted a great attention from the research and development community. Humanoid robots assist humans in daily life and replace them in hazardous working environments. Along with the development of actuators which are responsible for robotic motion, various sensor systems also have been investigated to improve the performance of humanoid robots [1][2]. Among these sensing systems, Micro Electro Mechanical Systems (MEMS) tactile sensors have been widely utilized to sense the grasping/impacting forces between robots' fingers and the grasped objects. The information obtained from tactile sensors is significant for feedback controls, pattern recognition, and dexterous handling and gripping objects [3][4].

Several sensing mechanisms have been deployed in tactile sensors such as capacitive, piezoresistive, piezoelectric, and optical sensors. Among these techniques, the piezoresistive effect in semiconductors such as silicon (Si), germanium (Ge), and silicon carbide (SiC) is one of the most common methods for mechanical sensing, due to its high sensitivity and simple structures [1-10]. Silicon piezoresistive cantilevers embedded inside elastomers such as poly dimethylsiloxane (PDMS) and poly methyl methacrylate (PMMA) have been applied for pressure sensing on robots' finger tips [5][6]. The large gauge factor and well-established fabrication technology of Si make it one of the most common materials for robotic sensing applications. However, the fabrication of Si based MEMS transducers requires expensive equipment and complicated processes such as micro-machining using cleanroom facilities. This drawback is indeed one of the crucial reasons making the cost of Si based sensors relatively high [11].

Recent studies have been aiming at developing MEMS sensors using low cost materials to solve the above bottle neck [11][12]. Graphite-on-paper (GoP) has emerged as a promising candidate for mechanical transducers [11-16]. The main advantages of GoP are its low cost, world wide availability, and simple fabrication process. The piezoresistive effect of GoP has been intensively investigated recently. Liu *et al.* reported a GoP force sensor with a sensitivity of 120 µN, using a screen printing technique [11]. Employing pencil drawing on paper, Kang reported large, tunable gauge factors of GoP varying from 15 to 50, indicating the capability of GoP for highly sensitive mechanical sensors [12]. Most of the previous studies only focused on the characterization of the piezoresistive effect in GoP. Only a small number of studies has demonstrated the feasibility of using the piezoresistive effect in GoP for sensing applications. One significant reason for this limitation in the practical applications of GoP is due to its direct exposure to environments which can be easily affected by ambient conditions such as humidity.

In this work, we propose for the first time, a novel platform for tactile sensors using plastic-laminated graphite-on-paper (LGoP). Plastic lamination and laser machining have been used for making low-cost microfluidic devices [13]. Plastic lamination not only improves the robustness of paper but also enhances its humidity-resistance, making it possible to embed LGoP inside elastomers for tactile sensing purposes. The platform proposed in this work demonstrates that LGoP has a high potential for simple, low cost mechanical sensing applications.

SENSOR CONCEPT AND FABRICATION

Concept of tactile sensor and its working principle

Figure 1 (a) shows the concept of the LGoP tactile sensor. The sensor consists of three parts assembled using epoxy. The pressure-transfer layer is made of PDMS with a thickness of 2.5 mm. The piezoresistive effect of the GoP was utilized for sensing the applied pressure. The bottom acrylic layer was used as the frame for the sensor. Figure 1 (b) describes the working principle of tactile sensing using LGoP. When a pressure/force is applied to the top surface of the PDMS layer, it is transferred to the sensing layer through the deformation of PDMS, bending the LGoP cantilever underneath. Due to the deflection of the LGoP cantilever, a strain is induced on the graphite layer, changing the distance between the graphite grains.
The electrical current flowing inside graphite layer is the tunneling current between the graphite grains. Accordingly, the relationship between the resistance of GoP and tunneling distance is [12][18]:

$$R(l) \propto e^{\beta l} \qquad (1)$$

where β is a function of the potential barrier height, and l is the distance between the graphite grains. Under strain, the tunneling distance is changed, leading to the change of tunneling resistance [18]:

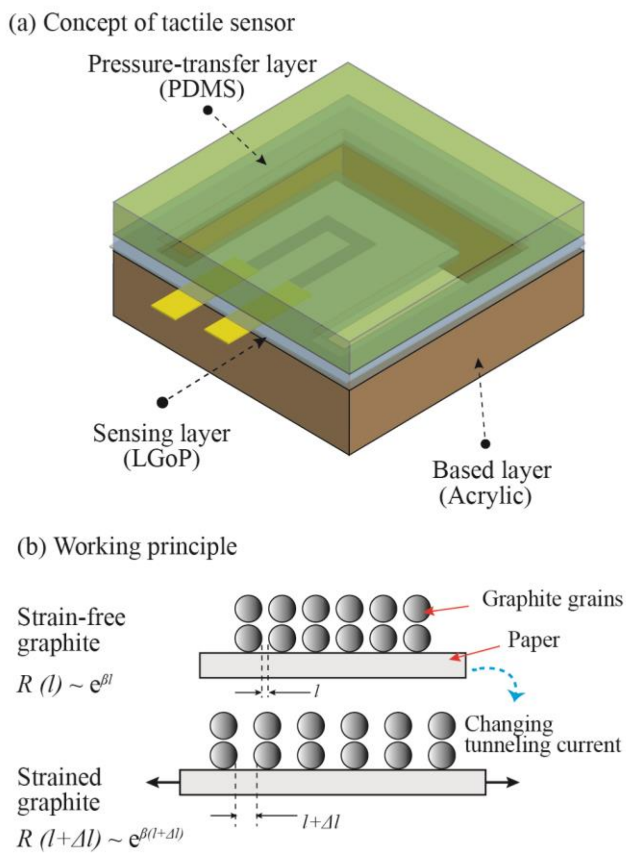

Figure 1: The concept of the tactile sensor using LGoP and its working principle.

$$R(l+\Delta l) \propto e^{\beta(l+\Delta l)} \qquad (2)$$

where Δl is the displacement between the graphite grains. As a consequence, the applied pressure can be obtained by measuring the resistance change of the GoP.

Fabrication of LGoP based tactile sensors

Figure 2 shows the fabrication process of the tactile sensor. The graphite layer was fabricated by drawing with a 2B pencil (Faber-Castel™) on commercial A4 paper. Graphite resistors were formed in a U-shape structure, with a length of 8 mm, a width of 2 mm, and their resistance was in the range of 100~200 kΩ. Aluminum tape (3M™) and highly conductive silver paste (186-3616, RS Components) were employed to make the electrodes of the graphite resistors (Fig. 2, step 1). Subsequently, a layer of paper was placed on the top surface of the graphite layer to prevent adhesion between the graphite and the laminated plastic film. Another layer of paper was also attached under the GoP layer to increase the distance from the graphite to the neutral axis of the composite beam (Fig. 2, step 2). These three paper layers were then laminated within two plastic films (Lowell Presentation System™) (Fig. 2, step 3). The thickness of each paper layer was 100 µm, while the thickness of the laminated layers of paper was 430 µm. A free standing LGoP cantilever with a dimension of 6 mm × 10 mm × 0.43 mm was formed by laser cutting (Speedy 300™, Trotecs) to improve the flexibility of the sensing layer (Fig. 2, step 4). In the next step, a PDMS layer with a thickness of 2.5 mm was coated using an acrylic mould. An acrylic frame was also made using a laser cutting technique. These three components of the LGoP, the PDMS top layer and the acrylic frame were then assembled using epoxy, forming the paper based tactile sensor (Fig. 2, step 5).

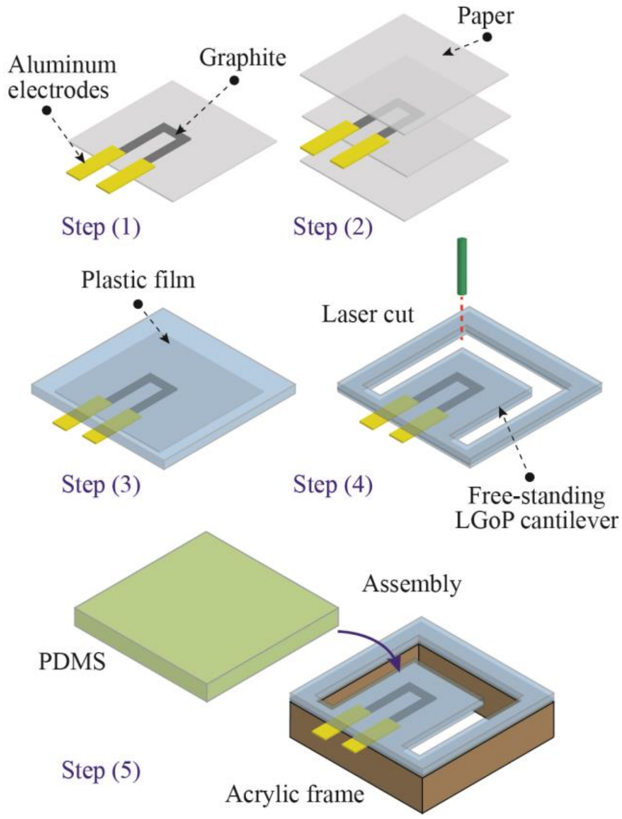

Figure 2: The fabrication process of the tactile sensor using LGoP

EXPERIMENTAL AND RESULTS

Characterization of LGoP and its piezoresistive effect

The mechanical properties of LGoP and the piezoresistive effect of graphite were characterized by using the bending beam method [7], in which an end of

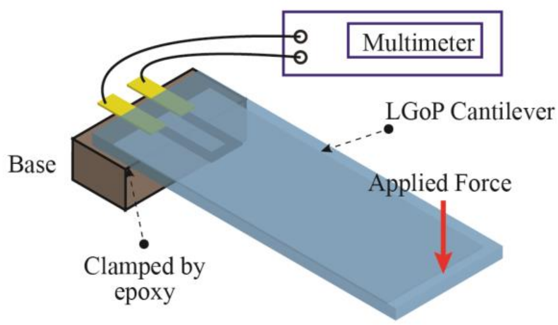

Figure 3: Experimental setup for characterizing the mechanical properties of LGoP and the piezoresistive effect of graphite.

LGoP cantilever was clamped, while the other end was deflected, Fig. 3. A LGoP-cantilever with dimensions of 10 mm × 40 mm × 0.43 mm was used in this experiment. The deflection of the tip of the cantilever was controlled using a two axis manipulator, while the applied force was measured by a high resolution balance (Ohaus™, Pioneer, PA4102). The resistance change of the graphite resistor was monitored using an Agilent™ 344110A multimeter. Figure 4 shows a good linear relationship between the applied force and the deflection of the LGoP. Accordingly, the stiffness (S) of the laminated paper was calculated using the following equation:

$$S = F/d \quad (3)$$

where F and d are the applied force and the deflection of the LGoP cantilever, respectively. Consequently, the stiffness of the laminated paper was found to be 12 Nm^{-1}. Young's modulus (E) of the LGoP is:

$$E = -4Fl^3/(wh^3d) \quad (4)$$

where l, w, h are the length, width and thickness of the LGoP, respectively. Using Eq. (4), Young's modulus of the laminated paper was found to be 3.5 GPa.

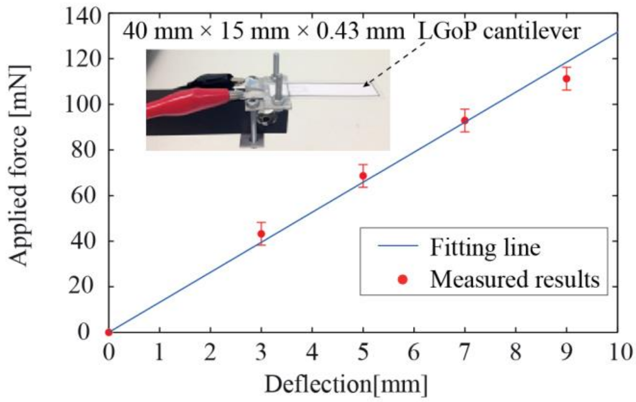

Figure 4: The relationship between the applied forces and the deflection of LGoP.

The strain induced on the graphite layer (ε) is:

$$\varepsilon = 12Flt/(Ewh^3) \quad (5)$$

where t is the distance from the graphite layer to the neutral axis of the LGoP cantilever. Figure 5 presents the relationship between the applied strains and the resistance change of the 2B graphite resistors, which shows a relatively good linearity.
The gauge factor can be calculated as:

$$GF = (\Delta R/R)/\varepsilon \quad (6)$$

where R, ΔR and ε are the graphite resistance, the resistance change, and the applied strain, respectively. As a result, the gauge factor of 2B graphite was calculated to be 26.2, which is consistent with the results reported previously by Kang [12]. This high gauge factor of

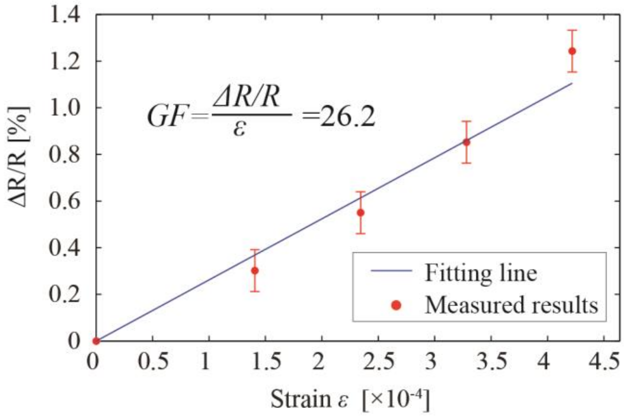

Figure 5: The relationship between relative resistance change of 2B graphite and the applied strains.

graphite indicates that GoP is a good candidate for low cost and highly sensitive transducers.

Demonstration of LGoP tactile sensors

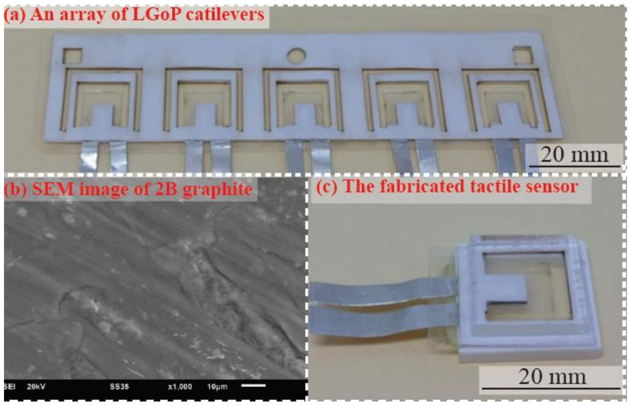

Figure 6: Photographs of fabricated tactile sensors.

Utilizing the piezoresistive effect of graphite and the lamination technique, LGoP tactile sensors have been developed with dimensions of 20 mm × 20 mm × 5 mm. Figure 6 shows photographs of the fabricated LGoP cantilevers and tactile sensors.

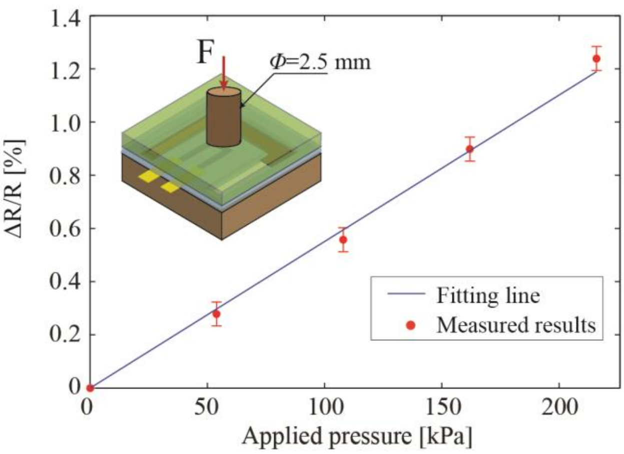

Figure 7: Response of the tactile sensors to the applied pressure.

By using the laser cutting technique, an array of LGoP can be easily fabricated, demonstrating the feasibility of mass production using the proposed method. The performance of the tactile sensor was characterized by applying pressure on the top surface of PDMS layer. Figure 7 shows the response of the developed tactile sensor to applied pressure varying from 0 to 200 kPa. As a result, the relative resistance change of LGoP was measured at 0.6×10^{-4} kPa^{-1}. From the signal to noise ratio, the resolution of the tactile sensor was 18 kPa.

CONCLUSION

In this paper, we reported on highly sensitive and low cost tactile sensors using plastic laminated graphite on paper. The laminated GoP not only enhances the robustness of paper but also improves its humidity-resistance, making it possible to embed LGoP inside elastomers for tactile sensing. Tactile sensors using LGoP sandwiched between a PDMS layer and an acrylic frame were fabricated and characterized, demonstrating the feasibility of using LGoP as a new platform for pressure sensing. With a high gauge factor graphite, a simple fabrication process, and a well-established laminating/laser cutting technique, paper based tactile sensors are good candidates for robotic applications in the future.

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