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Flexible pressure capacitor sensor based on polyurethane

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Abstract

Vehicles detection on the roads can aid in developing an intelligent transportations system that allows smooth movement while also reducing road accidents. There hasn't been a polymer flexible sensor with a low cost for vehicle detection till now. A polyurethane substance was sandwiched between aluminum top/bottom electrodes to create a vehicle sensor. The sensing mechanism relied on capacitance fluctuations caused by altering the electrode space when an external pressure was applied. The response was recorded at a pressure load of 0.60 MPa, equivalent to the pressure exerted by an automobile tire's contact area with the road. Due to its dimensions and mechanical adaptability, the sensor was exceptionally easy to install on the roadway. The sensor was embedded in the road and driven over to conduct a field test. Additionally, the signal from the tablet suggested that the sensing device could be used to wirelessly determine the axle, weight, and speed of an automobile while it is moving. The results show that, as a low-cost vehicle detector, the flexible pressure sensor might prove to be a helpful instrument for intelligent transportation management going forward.

Keywords: Pressure Sensor; Polyurethane vehicle detection; Intelligent transportation; Polymer's elasticity; capacitor sensor

1 Introduction

Both intrusive and non-invasive sensor technologies are commonly utilized for monitoring purposes. Using a laser sensor, a temperature sensor, or an image-based sensor, vehicles have been identified by changes in laser light intensity, temperature, or imaging traits connected to their appearance. These methods provide numerous opportunities for vehicle classification and traffic flow estimation[1]. Environmental factors such as fog, snow, rain, or shade adversely affect them, and the expenses associated with maintenance and installation of such sensors are substantial [2]. Induction loops have gained popularity in recent years due to their affordability and exceptional durability. The mechanism operates as a car traversing the loop alters the current in the wire. The disadvantage of installing these sensors is that the road surface may incur considerable damage. A recent study utilized anisotropic magnetoresistance sensors[3]. The vehicle's metal structure alters the Earth's magnetic field, enabling vehicle identification[4,5]. This sensing technology, however, is highly costly and susceptible to incorporating noise signals due to interference from other vehicles.

A pressure sensor composed of polymer materials has garnered significant interest from both academia and industry[6]. Its extensive operational range, minimal production costs, mechanical adaptability, and low processing temperature have all facilitated its recent surge in popularity[7]. The sensor comprises a layer of active polymer material situated between two electrodes. Variations in applied pressure result in changes to the resistance, capacitance, or electrical properties of the interposed layer, thereby modifying the electrical signal generated by the device, in accordance with the principles of piezoresistivity, piezocapacity, and piezoelectricity[8]. Usually built from sensing material systems, the layered constructions consist of poly(vinylidenefluoride-co-trifluoroethylene) (P(VDF-

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TrFE), polydimethylsiloxane (PDMS), a polymer-nanoparticle composite, or polymers injected with carbon nanotubes[9]. Because the flexible pressure sensor can fit the road, it is expected to be used in vehicle detection without compromising the infrastructure supporting transportation[10]. Furthermore, in contrast to an anisotropic magnetoresistance device, the pressure sensor remained impervious to the Earth's magnetic fields owing to the polymer's non-metallic composition. Operating under pressures from low-regime (0–0.01 MPa) to medium-regime (0.01–0.2 MPa), the literature has extensively studied flexible sensors for human health monitoring including heart rate monitors and EEG signals[11]. Among the several are weight measurements, collision events, and object tracking. Furthermore, the possible uses of a sensor with a larger measuring range in smart transportation have lately attracted much attention[12]. Ding et al[13]. illustrated a sensor device utilizing liquid silicone rubber and spiky spherical nickel particles. Furthermore, the potential applications of a sensor with a wider measurement range in smart transportation have recently generated a lot of interest. A nickel particle-based sensor's measured value ran from 0 to 7.5 MPa . Mohiuddin and van Ho[14] They developed a pressure sensor able to measure pressures up to 40 MPa by mixing multiwalled carbon nanotubes with a polyether ketone polymer matrix. The measurement ranges of these sensors are analogous to those of roadside automobile tires (0.4–0.7 MPa, Ref.), making them suitable for vehicle sensing in general . Nonetheless, the implementation of sensors in public transportation is constrained due to the substantial costs and complexities associated with the manufacturing process, particularly in achieving uniform dopant distribution within the polymer matrix[15].

In this paper, we describe the process of using polyurethane and thermal lamination to create a vehicle detecting capacitor sensor. The thickness of the polyurethane dielectric layer reduces when an outside force is applied to the sensor, so increasing the capacitance. The 0.65 MPa measurement range of the sensor is rather close to automotive tire pressure[16]. It was found that the optimal sensitivity of the sensor was 8 $*10^2$ kPa. The adaptability of the sensor helps simple installation on roads, so avoiding the need for road reconstruction.

2 Research method

Due to its simple construction, superior low power consumptions and its stability, a capacitor structure was used in Figure 1 to represent the flexible sensor. Aluminum (Al) foil electrodes (resistivity 2.6548 cm and the thickness about 30 m) acquired from Sigma-Aldrich were sputter-etched to eliminate any possible impurities or native oxide structures prior to being used in sensor manufacturing[16]. To put it briefly, 106 Torr of vacuum was applied to the Al foil while it was in an etching chamber. The chamber is then filled with 20 sccm of argon gas, and the etching pressure is set to 0.1 Pa. To create a plasma atmosphere and begin the etching process, an automatic tuning technique is used[17]. The power of etching is set to 30 W, which corresponds to a 0.5 nm/min etching rate. In our situation, we cleaned the Al foil for roughly 5–10 minutes to achieve a pristine conductive surface. Two aluminum electrodes were employed as the active layer, and a 100-micrometer-thick polyurethane polymer film, possessing a tensile strength of 38 MPa, was laminated twice at 80 °C, as depicted in Figure 2a. The sensor's dimensions were 70 mm by 70 mm at the point of electrode overlap[18]. This massive size was selected to be appropriate for an automobile tire tracking application. The sensor's connecting lead was then made by joining a copper wire to the electrode. Lastly, a plastic sheet was placed over the sensor and laminated at 80°C to protect it (Figure 2b). The laminator's rollers help to improve adhesive performance and flatten sandwiched polymers[19]. Images of the manufactured sensor in both regular (left) and flexible (right) modes are shown in Figure 2c. A microscopic cross-sectional image of the sensor was obtained to evaluate the uniformity of the sensor layer post-lamination. Since Figure 3 shows that each layer is well realized, the device layer is homogeneous[20].

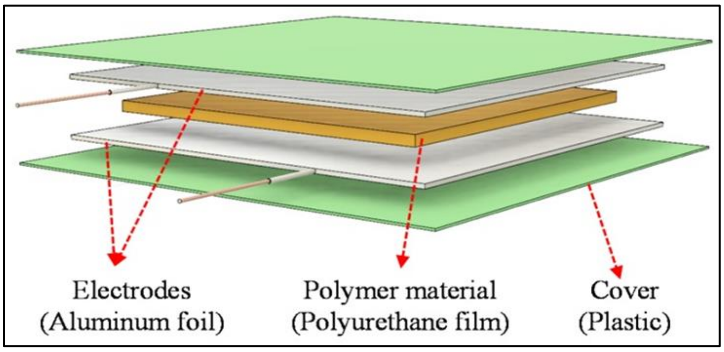

Figure 1 Capacitor structure of sensor

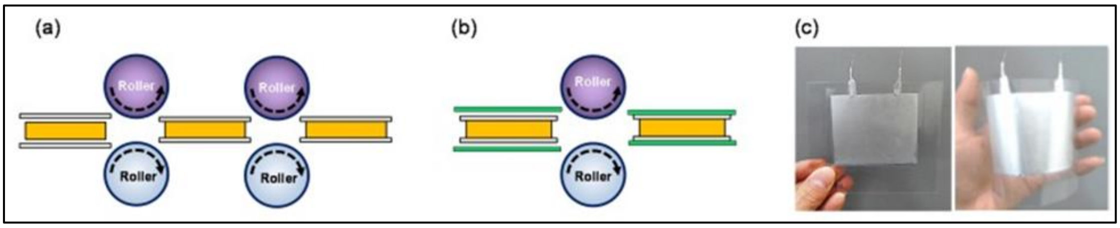

Figure 2 Polyurethane polymer

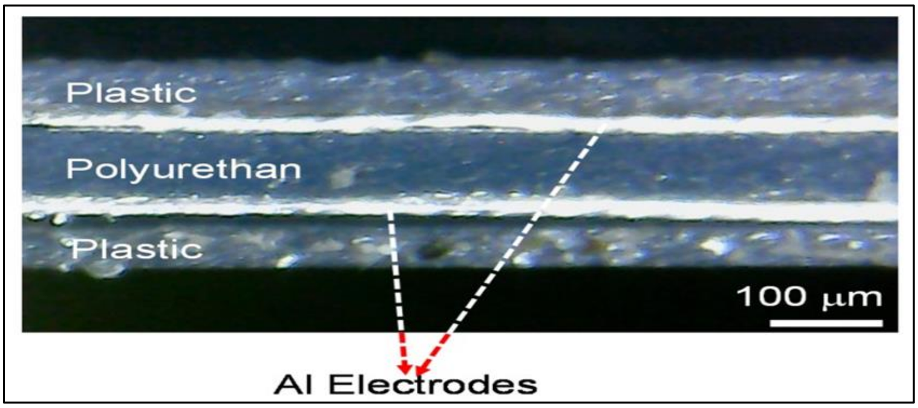

Figure 3 Layers of sensor

From 0 to 0.65 MPa, the sensor's dynamic range matched the pressure a car tire contacts the ground at[21]. Using a consistent experimental approach, devices with different polyurethane film thicknesses (200, 300, and 500 μm) were built to investigate how polymer thickness affects sensing.

3 Results

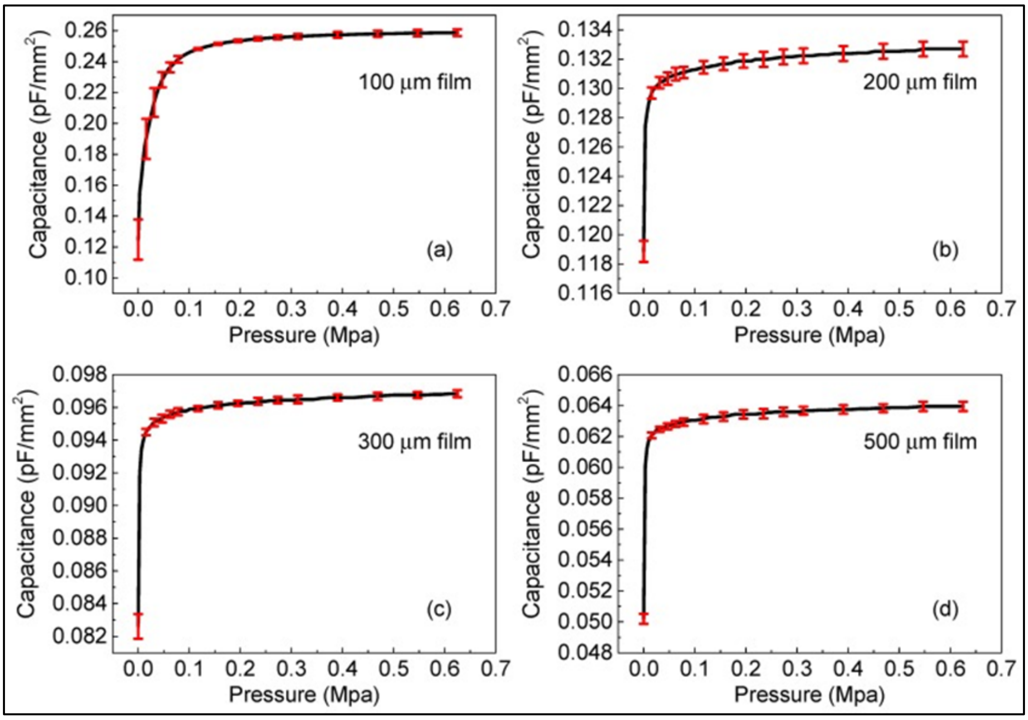

Figure 4 Demonstrates the attributes of capacitance pressure

The sensors' capacitance-pressure properties for pressures between 0 and 0.65 MPa are shown in figure 4. Initially capacitance values of 0.13, 0.19, 0.083, and 0.050 pF/mm^2 were displayed by the devices with polyurethane thicknesses of 100, 200,300, and 500 m respectively. A clear rise in capacitance was observed at low pressure; this tended to saturate as the applied pressure (p). Capacitive sensor systems have a similar property [17], demonstrating the quality of our device's sensors.

We performed supplementary analysis to enhance our comprehension of the operational mechanisms of the fabricated sensors. The capacitance of two parallel electrodes can be calculated using the following formula :

$$C=\varepsilon At \quad \ldots\ldots\ldots\ldots\ldots (1)$$

In this regard, t, A, and ε represent the dielectric constant, the overlapping area of the two electrodes, and the thickness of the dielectric layer—or the separation between the electrodes—respectively. Equation (1) shows that under applied pressure the following variables could be taken into account: (1) a variation in the dielectric constant of the dielectric layer, (2) a modification in the surface area of the device, or (3) a change in the separation between two electrodes. Still, mechanism (1) can be discounted as the dielectric constant of the polymer material used in the compression sensor stayed mostly constant at about 2. As the graph illustrates, the capacitance struggles to increase quickly if the device area changes. As a result, we assume that the operating mechanism is responsible for the decrease in thickness caused by the polymer's elasticity. Figure 5 depicts the sensor's proposed operation mechanism based on this assessment. Equation (1) demonstrates that the application of force to the sensor electrode results in a reduction of film thickness, thereby augmenting capacitance. Conversely, the capacitance returns to its original value upon the removal of the applied force from the interface.

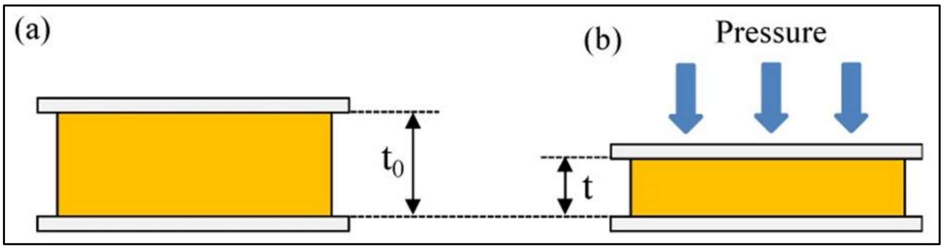

Figure 5 Polymer's elasticity

We estimated the variance in t with relation to external load pressure. Equation (1) let one derive the symbol t by applying the following equation: t equals εA/C. Figure 6, for a 100 m thick film sensor, illustrates, for instance, how capacitance and thickness change in response to externally applied pressure. Unlike the capacitance chance, the layer thickness t tends to drop with increasing pressure.

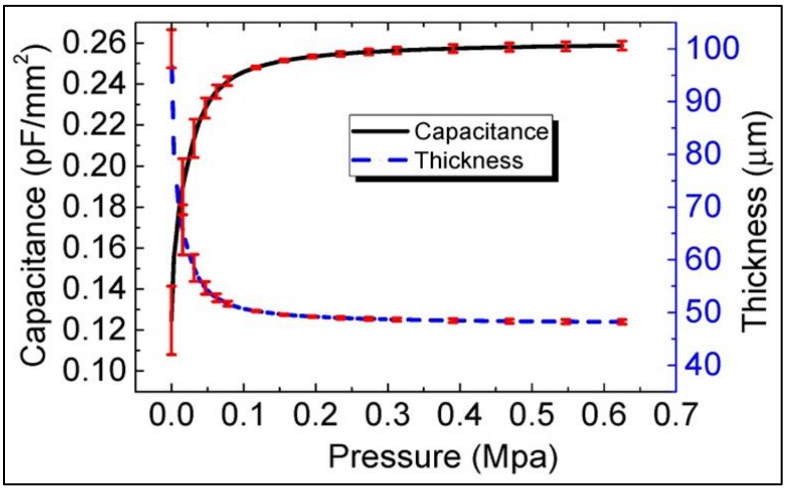

Figure 6 The variation in thickness and capacitance in response to externally applied pressure

Although the void designs produce measurement values of less than 0.1 Mpa, they have been often used to increase the sensitivity of sensors for human health monitoring. Using a polyurethane sheet with a tensile strength of 38 MPa, our study revealed that the sensor could measure pressure values up to 0.65 MPa.

The change in effective capacitance was determined by means of the next equation, so assessing the influence of the active thickness.

$$\Delta CC0=Cmax-C0C0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

While Cmax shows the maximum capacitance at p = 0.65 MPa, C0 stands for the capacitance at that point. The C/C0 notably dropped from 1.070 to 0.274, 0.172, and 0.116, respectively as the polyurethane's thickness increased from 100 to 200,300, and 500 m. This could be the result of a compact device's lower distance separating the upper and lower electrodes.The sensitivity (S) was computed with [21] the equation:

$$S=\delta(\Delta C/C0)\delta P \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Table 1 shows the S values for several film thicknesses and three pressure levels. Because of its higher C/C0 ratio, a thinner device has more S. Superior C/C0 and S performance are displayed by the 100 m-based sensor Comparable to previous pressure sensor systems, the 100 m based-sensor obtained a S value of up to 8 x 10^2 kPa at 0.003 MPa.

Table 1 Sensitivity spanning several pressure ranges and film thicknesses

The Pressure Rang in Mpa	The Sensitivity			
	100 µm	200 µm	300 µm	500 µm
0–0.04	2.32×10^{-3}	3.50×10^{-3}	4.33×10^{-3}	9.77×10^{-3}
0.04–0.3	3.98×10^{-2}	2.64×10^{-4}	2.89×10^{-4}	3.30×10^{-3}
0.30–0.65	1.20×10^{-4}	4.57×10^{-5}	4.07×10^{-5}	7.35×10^{-4}

One could assess the repeatability of the change in capacitance values under constant p (Figure 7) by means of a 100 m based-sensor responding to a constant p of 0.65 Mpa. Release of the pressure in the first cycle did not cause the capacitance at p = 0 Mpa to return to its starting value. That would come from the deforming polyurethane film. But as Figure 7a shows, the second cycle obviously exposed the repeatable characteristics. Furthermore investigated were pressure-sensing properties for several p values: 0.08, 0.2, 0.65, 1.0, and 1.5 Mpa. As Figure 7b shows, the sensor reacts regularly and consistently. Usually, one can define the sensors as pressure-resistant and vehicle-sensing-capable.

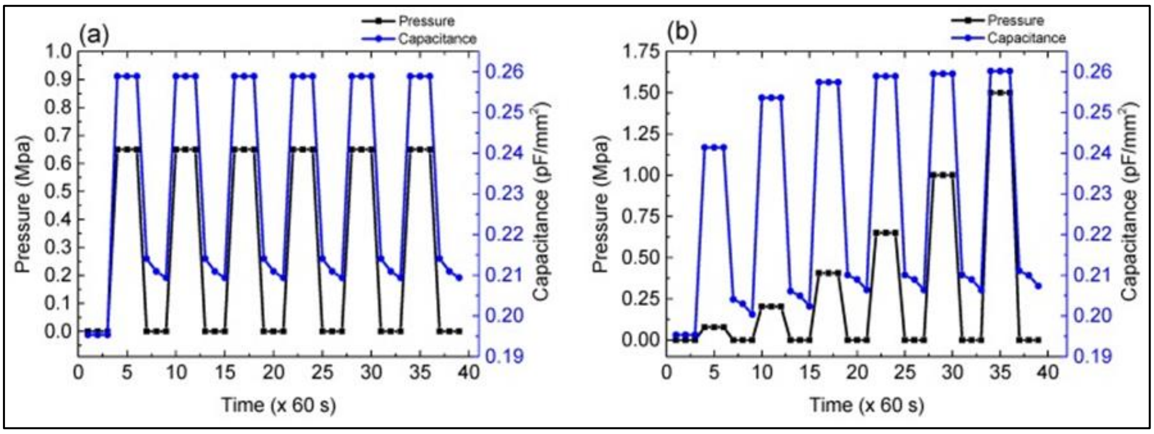

Figure 7 The sensors pressure-resistant and vehicle-sensing-capable

Figure 8 shows the adaptability of a polyurethane sensor tested with varied bent radii of curvature between 200 mm and infinite (normal state). Its capacitance was. Figure 8 indicates that the polyurethane sensor can be used correctly at bent radius more than 500 mm by showing a rather steep rise in capacitance from 200 to 500 mm with the increase saturating at bent radius more than 500 mm. We would want to underline that the flexible character of the sensor facilitates its efficient change to the surface roughness of asphalt concrete, which is widely used to build roads nowadays.

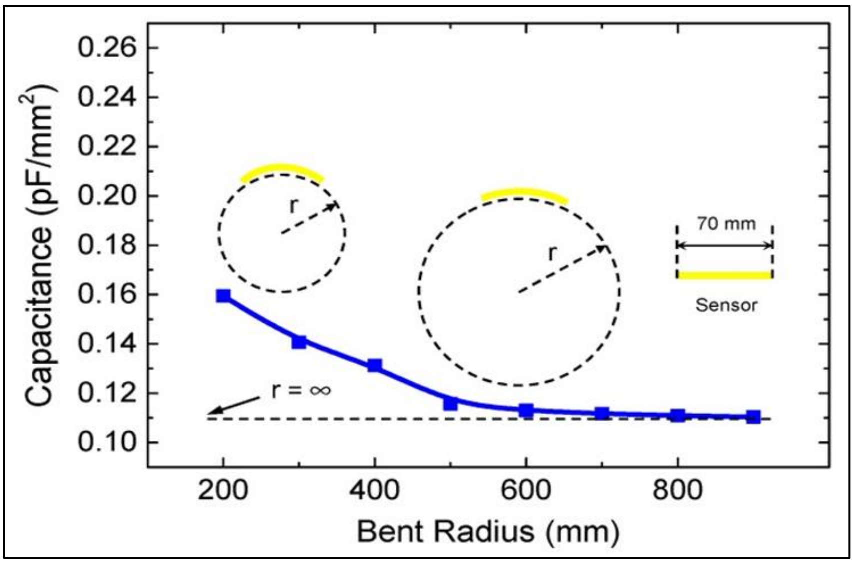

Figure 8 A rather strong rise in capacitance between 200 and 500 mm, with the increase saturating at bent radius more than 500 mm

4 Conclusion

A flexible sensor made of polyurethane and laminating technique was developed. The operational mechanism turned out to be the t dielectric layer's thickness decreasing. Based on the electrical evaluation, the 90 m-based sensor shows improved C/C0 and S performance. The capacity of the sensor to detect pressures up to 0.65 MPa points to possible application. Its mechanical adaptability and great scale help explain Install the sensor on the road line; it is easy. Using the program on the tablet computer allows one to ascertain the weight, speed, and axle of the vehicle. Developing a cheap smart transportation management system seems to depend on the flexible pressure sensor as a promising technology. Based on the here reported findings. The sensor systems do, however, obviously have some problems, including low measurement and poor estimated V accuracy, which suggests that more work—especially in the context of algorithm development—is needed to overcome these constraints. More testing scenarios including those involving a larger weight range, a real road, or various kinds of vehicles have to be conducted to evaluate the developed sensor device systems for future validation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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