Electrical and Mechanical Properties of PEDOT:PSS Strain Sensor based Microwave Plasma modified Pre-vulcanized Rubber Surface

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Abstract. Poly(3,4-ethylenedioxythiophene) doped with poly(styrenesulfonate) (PEDOT:PSS) conductive polymer has been extensively used in various applications including flexible electrode and stretchable sensor. This study reports the electrical and mechanical strain behaviours of PEDOT:PSS deposited on pre-vulcanized rubber substrate, which is modified surface by microwave plasma. The effect of plasma treatment cycles on adhesion of PEDOT:PSS coated pre-vulcanized rubber and conductivity have been investigated. The results show a uniform PEDOT:PSS film on rubber surface after treating with microwave plasma. The electrical conductivity slightly increases by increasing treatment cycles. In addition, an electrical strain and mechanical strain increase up to 60 and 50%, respectively under 4 treatment cycles.

1. Introduction

Recently, flexible strain sensors have become highly increasing demand for their board applications in the field of health monitoring device, electronic skin and soft robot [1, 2]. Among the soft polymeric materials, poly(3,4-ethylenedioxythiophene) doped with poly(styrenesulfonate) (PEDOT: PSS) is widely applicable in flexible electronic devices [3]. By coating on the elastomeric substrate such as polymethyl methacrylate (PAMA), polyvinyl alcohol (PVA), poly(dimethylsiloxane) (PDMS) and rubber, it can be used as stretchable electrodes, pressure and strain sensors [3, 4]. As the substrate material of strain sensor, natural rubber that has a good elasticity, high strength and large elongation, giving a good recovery to original structure after releasing strain [5, 6]. To make conductive rubber, layer of PEDOT:PSS on rubber can be simply made by using spin coating technique. Plasma treatment to a surfaces cleaning and etching was used to modify a wettability of the surface before prepared the thin film on substrate.

In this study, we investigate the mechanical strain-responsive electrical behaviours of PEDOT:PSS films coated on natural rubber. The effect of plasma-treated rubber surface on electrical resistance was observed.
2. Experimental

The strain sensor was prepared by spin coating PEDOT:PSS on a pre-vulcanized rubber (received from S.K. Polymer, Thailand). Briefly, the rubber (0.5 mm thick) was attached on glass substrate, cleaned by rinsing with deionized water and dried with nitrogen gas. To remove an organic residues and increase the adhesion of PEDOT:PSS on the rubber surface, the pre-vulcanized rubber was treated under microwave plasma for 15 sec. The optimized condition was done by varying the treatment cycles ranging from 1 to 4 cycles. Then 1.1 wt% of PEDOT:PSS was spun on the substrate with spin speed of 4000 rpm for 30 sec and annealed on a hotplate at 60 °C for 30 min. After that, the gold electrode was attached on the top of PEDOT:PSS to make an electrical contact. Finally, the device was peeled off from the glass substrate and cut into a fixed size of 5 x 35 mm², as shown in Figure 1(a).

The initial electrical conductivity of strain sensor was measured with Keithley 2400 source meter. Uniaxial stretching tests of the sensor were conducted using a homemade tensile system equipped with an electrical contactable jig for in-situ resistance measurements (Figure 1b). The change in resistance by uniaxial tension was measured at constant strain rate until it reaches breaking point. The relative resistance change ($S_R = \Delta R/R_0$) was calculated based on the initial resistance $R_0$ and the change in resistance $\Delta R = R_a - R_0$, where $R_a$ the actual resistance at a given strain value.

3. Results and discussion

Optical images of PEDOT:PSS coated on pre-vulcanized rubber without and with plasma treatment are showed in Figure 2a. Due to its high hydrophobic of rubber surface [7], this made no adhesion of
PEDOT:PSS on the bare rubber. Under microwave plasma treatment, there is an evidence of a light blue surface of PEDOT:PSS appeared on the substrate. The electrical resistance slightly decreased by increasing the treatment cycles as demonstrated in Figure 2b. With a fixed dimension size of 5 x 35 mm², the conductive rubber shows a measured resistance of 5.70 MΩ, 5.07 MΩ, 4.16 MΩ and 3.70 MΩ for 1, 2, 3 and 4 plasma treatment cycles, respectively. The plasma cleaning can be increased a wettability of the natural rubber surface and enhanced the on-surface coating. With increasing treatment cycles, a higher surface energy was observed as indicated higher adhesion of PEDOT:PSS on the rubber surface.

To investigate the variation of electrical properties of the strain sensor under mechanical stress, the sensing was tested in the stretching mode. Figure 3 shows the relative resistance change \( (S_f) \) as a function of tensile strain \( (\varepsilon = \Delta L/L_0, \) where \( \Delta L \) is the change in the actual length at a given strain and \( L_0 \) is the initial length) for the different samples prepared with different plasma treatment cycles. The average resistance slightly decreases at the beginning, as seen in inset of Figure 3a, then it appears linearly increases and follows by drastic increases in the further elongation, finally the destruction of conductive network is occurred. The decrease in electrical resistance at the beginning of stretching may be due to a strain-induced the growth of conductive region of PEDOT:PSS by coalescence of conductive PEDOT-rich cores [8]. The increasing mechanical strain results in the loss of conductive path which causes difficult electron pass, and a crack generation lead to electrical breakdown at higher strain.

Figure 3b presents the maximum strain and gauge factor \( (GF = S_f/\varepsilon) \) as a function of plasma treatment cycles. However, the natural rubber will be burned for further increase number of plasma treatment more than 4 cycles. Generally, the change in resistance of the PEDOT:PSS films on stretching elastic substrate depends on many factors such as the cracks generated by applied strain, the change in geometrical shape of the films and PEDOT:PSS-substrate interaction. Among all these factors, the PEDOT:PSS-rubber interaction is the most important parameter that influences sensing sensitivity of strain sensor after plasma treatment.

![Figure 3](image)

**Figure 3.** (a) Relative resistance change of PEDOT:PSS coated on rubber with different plasma treatment cycles. (b) Sensitivity and maximum mechanical strain of strain sensor based conductive rubber.

### 4. Conclusions

Flexible strain sensors were fabricated by spin coating PEDOT:PSS on pre-vulcanized rubber films. The microwave plasma treatment was used to enhance the hydrophilic of rubber surface which results in a
homogeneous distribution of PEDOT:PSS on the surface of rubber. A good adhesive of PEDOT:PSS on natural rubber was observed after 4 treatment cycles (15 sec treatment interval time) with initial resistance of 2 MΩ. In the stretching mode strain sensor, the average resistance decreased and stretchibility of the strain sensor improved with an increase in plasma treatment cycles. The electrical and mechanical strain increase from 40 and 42% up to 60 and 65% for 1 and 4 treatment cycles, respectively. These results demonstrate that the conductive rubber can be used as a promising candidate for strain sensor or stretchable electrodes.

5. References
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