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Realizing Mechanically Robust ITO and PEDOT:PSS by Reducing Substrate Thickness to as Thin as 1.4 µm

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Abstract

Flexible transparent conductors have recently become very popular not only because of the need for flexible optoelectronics, but also for bio-applications. For bio-applications, the material should have stable properties under bending since biological organs have a complex surface and shape. In this research, we achieve stable characteristics of transparent electrodes under bending by using two approaches: reducing the substrate thickness as thin as 1.4 µm and using a polymer conductor with a low Young Modulus. For the evaluation of the electrode stability under bending, two transparent conductors, PEDOT:PSS and ITO, are evaluated with substrates thicknesses ranging from 1.4 to 125 µm with applied strains of up to 20%. Having a low Young Modulus, PEDOT:PSS, deposited on 1.4 µm-thick substrate, shows a negligible resistance change of only 0.38%. While for ITO, cracks are observed on the film, which lead to a higher resistance change.

1. Introduction

For bio-applications, a low resistance and a highly flexible transparent electrode are important considerations to obtain a high quality bio-signal, for applications such as microscope imaging using microelectrode arrays [1] and, neurosignal measurements for optogenetics [2]. In addition, the device should be robust to bending because biological organs have a curvy shape, such as the brain, heart, lung, or eye. During bending, strain will develop on the electrode. The equation, which describes the strain induced on a thin film under bending, is shown in eq. (1) [3].

$$\varepsilon_f = \left(\frac{t_f + t_s}{2R}\right)\frac{(1+2\eta+\chi\eta^2)}{(1+\eta)(1+\chi\eta)} \qquad (1)$$

Where $\eta = t_f / t_s$ and $\chi = E_f / E_s$

ε_f = strain induced on the thin film
R = applied bending radius
E_s = Young's Modulus of the substrate
E_f = Young Modulus of the thin film
t_s = substrate thickness
t_f = thin film thickness

Generally, the thickness of thin film is much less than the thickness of substrate. Therefore, in eq. (1), the most dominant variable is the substrate thickness. Thus, a naturally brittle material can endure a more severe folding or a smaller bending radius without significant degradation due to the sufficiently low strain incurred. For instance, K. Chiba *et al* reported that ITO could endure a 4 mm bending radius by using a 75 µm-thick substrate [4]. Furthermore, by reducing the substrate thickness into 1 µm, an all-oxide transistor can still work when being bent into a 50 µm bending radius [5]. However, until now, there is no report on the investigation of ITO or PEDOT:PSS under mechanical bending by reducing the substrate thickness systematically.

In this research, we investigate the bending durability of ITO and PEDOT:PSS by systematically reducing the substrate thickness of PEN from 125, 25, and 12 µm. Additionally, we use an ultrathin 1.4 µm-thick PET substrate to obtain even higher flexibility. By performing mechanical bending test and by reducing the substrate thickness from 125, 25, and 12 µm, the abrupt resistance change of ITO and PEDOT:PSS shifts from 3.0 mm to 2.1 mm and to 1.5 mm, respectively. Additionally, by performing a mechanical buckling test on 1.4 µm-thick substrate, PEDOT:PSS shows a very small resistance change ($\Delta R/R_0$) of only 0.38%, while ITO shows higher resistance change, 17%.

2. Reducing Substrate Thickness from 125, 25, and 12 µm

For these substrate thicknesses, mechanical bending test were conducted on both transparent conductors. In this test, the transparent conductors were loaded in compression as illustrated in inset of Fig. 1. Upon bending, the resistance was measured for each of applied bending radius. The minimum applied bending radius is 0.3 mm or equal with 20.9% of strain on PEDOT:PSS and 20.6% of strain on ITO.

From Fig. 1a, it is seen that by reducing the substrate thickness, the rapid increase of resistance change of both ITO and PEDOT:PSS shifts into smaller bending radius. This result agrees with eq. (1), in which the induced strain on a thin film will be lower by reducing the substrate thickness. In the other words, applying smaller bending radius is required to induce a larger strain on a thin film with thinner substrate.

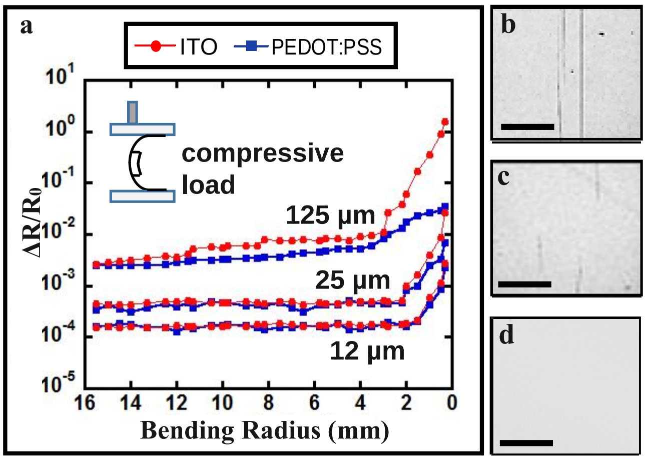

Fig. 1 a) Resistance change of ITO and PEDOT:PSS thin film, deposited on 125, 25, and 12 µm-thick substrate, as a function of applied bending radius. b) Cracks on the 125 µm-thick and c) 25 µm-thick PEN substrate d) no observable cracks on the 12 µm-thick PEN substrate. Scale bar: 100 µm.

It should be noted that failure of the PEN substrate itself affects the resistance change of both ITO and PEDOT:PSS as we found that the substrate itself starts to form buckles or cracks, shown in Fig. 1a-c, at small bending radii. For 125 µm-thick substrate, it occurs at a 1.5 mm bending radius, while for 25 µm-thick, is at 0.3 mm. For 12 µm-thick, no cracks are observed on the substrate at a 0.3 mm bending radius.

3. Reducing Substrate Thickness to 1.4 µm

To achieve a higher flexibility, reducing the substrate thickness below 12 µm is necessary. However, as the substrate is reduced to as low as 1.4 µm, mechanical bending tests becomes impractical. Hence, we use the mechanical buckling method to bend the transparent conductors. This buckling method is a common method to engineer a stiff material to be stretchable [6]. In addition, the buckling method can also be used to create an extreme bending radius, reaching micrometer scale, on a compliant plastic substrate [7].

To create buckles on 1.4 µm substrate, the elastomer, consisting of 1 mm thick PDMS and 50 µm of elastic acrylic sheet, was pre-strained at 50%. While maintaining the pre-strain, the transparent conductor, deposited on a 1.4 µm-thick substrate, was laminated on top of the elastomer. After lamination, the pre-strain was released slowly, resulting in buckles to relieve the compression energy produced by the relaxation of the pre-strained elastomer.

In this test, the resistance of the thin films is measured before and after releasing the pre-strain. The result, shown in Fig. 2a, shows that PEDOT:PSS exhibits a high stability by having only 0.38% of resistance change, whereas ITO shows a 17% resistance change. SEM images of this buckled ITO thin film, shown in Fig. 2c, reveal cracks on the film. These cracks lead to a higher resistance change on the buckled ITO thin film. However, a 17% resistance change of ITO is still considered as small enough change since it means that the degradation is only 1.17 times of the initial resistance. Therefore, this highly deformed ITO should still be sufficiently enough to be used for bio-signal recording without severely affecting the measurement.

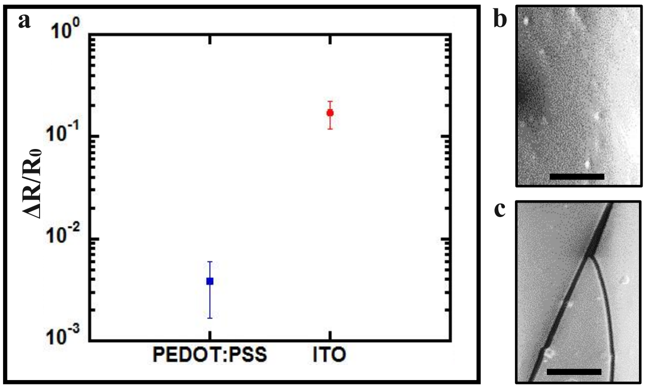

Fig. 2 a) Resistance change of the ITO and PEDOT:PSS thin films, deposited on 1.4 µm-thick PET substrate, after releasing the pre-strain. b) SEM images on buckled PEDOT:PSS and c) ITO after releasing pre-strain. Scale bar: 4 µm.

4. Conclusions

By reducing the substrate thickness from 125 to 12 µm, ITO and PEDOT:PSS can be bent into a smaller bending radii while having a smaller resistance change. Using the mechanical buckling method on 1.4 µm thick substrate, the film is bent into a micrometer bending radius in several regions of the film. At this very small bending radius, PEDOT:PSS, having a low E_f of 3 GPa, exhibits very stable performance by showing a negligible resistance change. On the other hand, ITO, having a high E_f of 118 GPa, shows a higher resistance change since cracks develop on the film. This study can pave the way of electronic technology to the compliant bio-electronic device with durable performance in diagnosing or monitoring bio-signal.

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