DEVELOPMENT OF CONFORMAL PDMS AND PARYLENE COATINGS FOR MICROELECTRONICS AND MEMS PACKAGING

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ABSTRACT

There is a growing demand in the development of small-scale devices in microelectronics and microelectromechanical systems (MEMS). Packaging and reliability of such devices are of great concern as they introduce a number of unique packaging issues that are distinct and different from typical electronic packaging applications. In addition, the packaging or encapsulation materials are often exposed to harsh environments, for which their performance is drastically degraded. Importantly, such devices become lighter and smaller, precluding the use of conventional packaging materials and schemes. Given that, surface protective coatings can provide an innovative solution for some of the aforementioned issues. Polymers have indeed shown such a potential for use either as a standalone coating, or an intermediate layer for the subsequent harder, stiffer coatings. In this study, we explore processes and properties of the three coating systems: i) PDMS, ii) Parylene (para-xylylene), iii) Parylene/PDMS.

In particular, parylene coating on PDMS is a focus of this study. The parylene coating having much higher mechanical properties than PDMS provided a way to enhance the surface properties of this PDMS. Proper surface modification of PDMS via oxygen plasma seemed to be essential to generate desirable microstructures of parylene coating. Mechanical properties of such coatings are systematically examined via a nanoindenter. The dynamic nanoindentation is also employed to assess viscoelastic properties, as well as depth-dependent mechanical properties. While characterizing the films using the nanoindentation, the substrate effect influenced the indentation data. In addition, extensive surface characterizations are carried out using atomic force microscope (AFM), scanning electron microscope (SEM), and optical microscopy.

INTRODUCTION

The technological developments in microelectronics and MEMS have rapidly advanced in the past few years. One of the most difficult challenges along with these developments is assembly and packaging of the devices that often require novel materials and process technologies. New developments also demand lower cost materials and processes with improved reliability. Furthermore, continuous migration of devices to smaller features contends a very aggressive packaging technology.

Polymers have been widely used as a packaging material [1]. These materials can, however, be degraded easily in certain environment due to severe erosion and surface roughening, creating long-term reliability concerns. Due to inherent advantages of using polymeric materials including flexibility, processibility, low density, and electrical properties, it would not be practical to replace them with alternative materials such as ceramics or metals. Several efforts have thus far been explored to enhance inherent polymer durability, and protective coatings using stable oxides are one of the options.

One thrust area in polymers is to deposit them as a thin film/coating on various types of substrates for a surface protection and functionality. In this case, they must exhibit chemical compatibility, low residual stress, good adhesion, and good solvent resistance. In fact, PDMS has shown great potential as a coating material. It is easy to fabricate, inexpensive, transparent and biocompatible [2, 3]. But the

film uniformity and chemical/mechanical resistance has yet to be satisfactory to be used in harsh environment. Parylene has shown a great promise as a conformal coating onto any geometrical shape of the surface even with holes and cracks. Parylene coatings have also low permeability to moisture and gases such as nitrogen, oxygen, carbon dioxide [4-6]. There are several different types of parylenes available; namely, type C, N, D and F that have been considered in many commercial applications, such as dielectric films and encapsulation of semiconductor devices. Among those candidates, parylene C coating has a lower gas permeability and diffusivity than the others. This good barrier characteristic of parylene C is attributed to the polarity of the chlorine atom attached to the phenyl ring, which increases the intermolecular forces [7]. In addition, parylene C is very ductile so that the conformality can be better. It, however, has been suspected for a poor adhesion and a difficulty in growing thick coatings.

We therefore explore processes and properties of the two polymer systems, and ultimately their bilayer structure consisting of parylene C and PDMS. In this way, we can utilize the advantages of each individual coating concept while self-compensating for the weaknesses to promote a 'synergistic' effect between them. The objective is to establish the structure-property relationships of the polymer coatings from known processing parameters so that their properties can be tailored for optimum performance. Nanoindentation techniques are employed to study mechanical properties of the polymer coatings [8, 9]. These mechanical performances will be correlated with microstructures of the coatings using a variety of characterization techniques such as atomic force microscopy (AFM), scanning electron microscopy (SEM), optical microscopy, and contact angle measurements.

EXPERIMENTAL PROCEDURE

PDMS coating was prepared by spinning its solution (Gelest, PA) dropped on the substrate. Curing is immediately taken place by moisture absorption during spinning and drying. Several layers of the coating were deposited to grow the desired thickness. For the parylene coating, we used a parylene C dimmer (di-chloro-di-para-xylylene) which is a most common form of parylene. The parylene deposition process consists of three steps: vaporization, pyrolysis and deposition. The condition for vaporization is 150 ℃ and 1 torr, at which parylene is in its dimer form (di-para-xylene). The pyrolysis step follows with a condition at 690 ℃ and 0.5 torr where parylene is changed to a monomer (para-xylene). Polymer (poly-para-xylylene) is finally coated on the substrate placed at 35 ℃ and 0.1 torr. For this study, the parylene was deposited with the rate of 5 μm/hour (based on 1.5 μm/g), and measured thickness was slightly higher than this predicted rate. For the bilayer system, PDMS was first deposited, onto which the parylene layer is coated. The PDMS surface was also modified to hydrophilic surface by oxygen plasma prior to the parylene deposition in order to improve adhesion [10, 11].

The coated samples were examined by a variety of characterization tools such as AFM, SEM, and optical microscope. Surface modification and properties were also monitored using a contact angle meter. In particular, mechanical properties of the coatings were systematically examined with the aid of a nanoindenter (Hysitron TriboIndenter, MN). The mechanical performance provides the quality of the coating. This instrument also has an *in-situ* AFM imaging capability.

In nanoindentation study, we also employed a dynamic testing by superimposing a small, sinusoidally varying AC signal on top of a DC signal that drives the motion of the indenter. By analyzing the response of the system by means of a frequency, specific amplifier data are obtained. This allows the measurement of contact stiffness at any point along the loading curve. The dynamic system can be modeled through mechanical analogs consisting of springs and dashpots, in which the storage modulus (E') and loss modulus (E'') are given by:

$$E' = \frac{k_s \sqrt{\pi}}{2\sqrt{A_c}} \; ; E'' = \frac{\omega C_s \sqrt{\pi}}{2\sqrt{A_c}} \; ; \tan\delta = \frac{E''}{E'} = \frac{\omega C_s}{k_s} \qquad , \quad (1)$$

where k_s is a spring constant, C_s a damping coefficient, δ a phase angle between stress and strain, ω a frequency of oscillation, and A_c a projected area of contact. This analysis would be useful in mechanical characterization of viscoelastic polymers.

RESULTS AND DISCUSSION

Typical microstructures of the parylene coatings contain the "bubbles" as shown in Fig. 1 (a). It was also observed that these bubbles are growing and combining as the parylene coating thickness increases. The number of those bubbles were, however, reduced when the parylene was deposited on PDMS whose surface was oxygen plasma treated (Fig. 1 (b)). The origin of this bubble structure and its effect on the parylene properties are not clear at this point.

In fact, surface modification of the underlying PDMS seemed to play an important role in controlling the microstructures of the parylene coatings as shown in Fig. 2. Three different surface conditions were prepared prior to the parylene coating via a vapor phase deposition. Without oxygen plasma treatment, the parylene surface was very rough as shown in Fig. 2 (b) whereas the oxygen plasma treated surface resulted in rather smooth surface of the parylene. The oxygen treated surface even exhibited a smoother surface than that on the flat glass slide (Fig. 2 (c)). Table 1 shows the domain size and surface roughness of the parylene coatings deposited on three different substrate conditions.
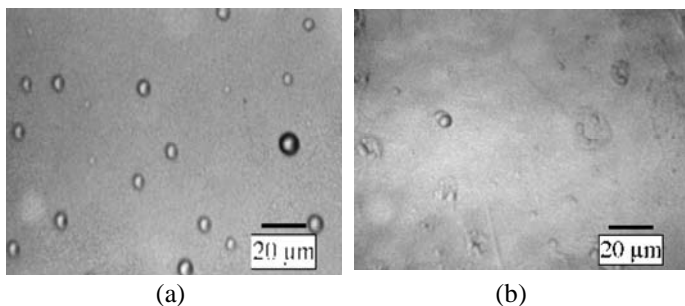
Fig. 1: Optical microscope images of the parylene coating deposited on: (a) Glass slide; (b) O_2 plasma treated PDMS. Note the 'bubbles' in the film.
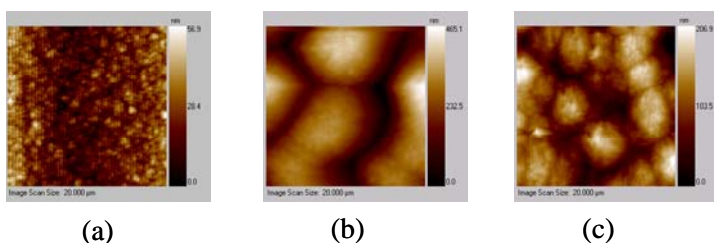

Fig. 2: AFM images of the parylene coating deposited on: (a) O_2 plasma treated PDMS; (b) No O_2 plasma treated PDMS; (c) Glass slide.

Table 1: Domain size and RMS roughness comparison.

	Parylene C /O₂/PDMS	Parylene C /PDMS	Parylene C only	note
Domain size	1~2 µm	10~15 µm	5~8 µm	Parylene C film thickness = 28 µm
RMS Roughness	10.42 nm (±3.37)	76.77 nm (±10.02)	42.74 nm (±9.49)	15 areas (20 µm X 20 µm)

The polymer coatings were also deposited on small microelectronics circuitry to see the conformality of the coating on complex geometry. Cross-sectioned specimens were prepared and observed through optical microscope and SEM. As shown in Fig. 3, PDMS dramatically relaxed the surface roughness, which makes the subsequent coating process easier to form uniform coverage. On the other hand, the parylene C coating displayed superior surface coverage by providing almost the same thickness over the entire areas of the components (top, side, bottom). The parylene coating cannot, however provide more relaxed surface on the complicated geometry, and can take longer time to reach the same level of the coating thickness as that of PDMS. As a result, the hybrid approach can be beneficial by utilizing the advantages of both coating systems as mentioned earlier.

Higher magnification SEM images of cross-sectioned coatings are shown in Fig. 4, where parylene and PDMS show relatively good adhesion with no apparent delamination. In addition, preliminary scotch tape and scratch tests did not produce any delamination. More quantitative adhesion tests are underway to study the interfacial properties for further enhancement of the bilayer coating systems.
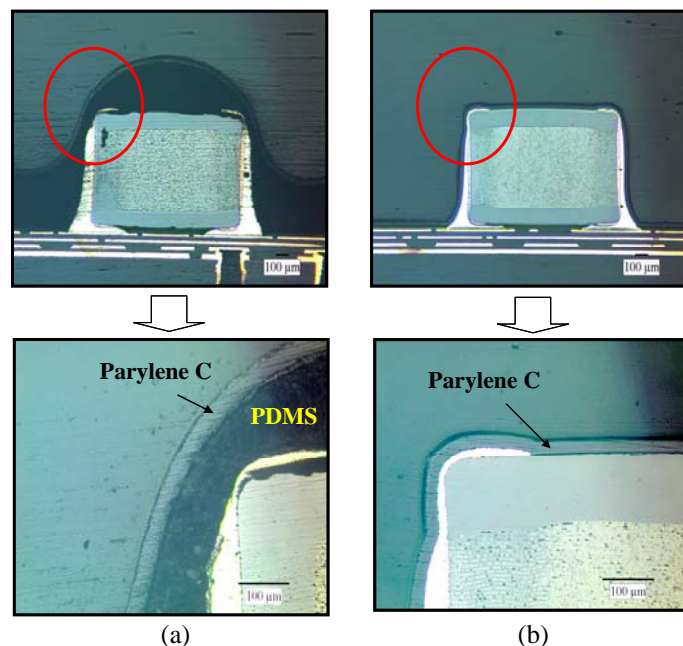

Fig. 3: Optical microscope image of cross-sectioned coated-components on a circuit board: (a) Parylene/PDMS; (b) Parylene only.
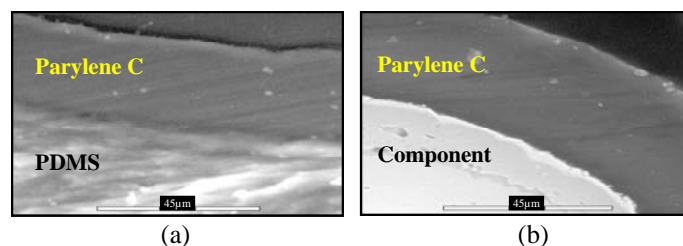

Fig. 4: SEM image of two different coating systems on a component: (a) Parylene/PDMS; (b) Parylene.

In order to understand mechanical performance of the aforementioned coating systems, the nanoindentation technique was employed. One difficulty here is that nanoindentation on a top parylene coating will be likely to be influenced by the compliant PDMS (modulus ~ 3.4 MPa, hardness ~ 2.6 MPa, [12]). Top indentation clearly exhibited this substrate effect as shown in Fig. 5, wherein the parylene properties were much underestimated due to the underlying PDMS layer. When no PDMS was incorporated at the substrate-coating interface, the apparent modulus and hardness of the parylene coating were higher.

For this reason, the side indentations were performed on the polished cross-sectioned areas (Fig. 5). For no PDMS case (i.e., parylene only), the top and side indentation results were very close, indicating no effect from the substrate. With no substrate effect, the values of elastic modulus and hardness

of parylene were around 3.1 GPa and 130 MPa, respectively. This substrate effect is much pronounced for elastic modulus due to the fact that the elastic mismatch between the film and the substrate was greater, and that elastic deformation region is extended farther, as compared to the plastic deformation (i.e., hardness).
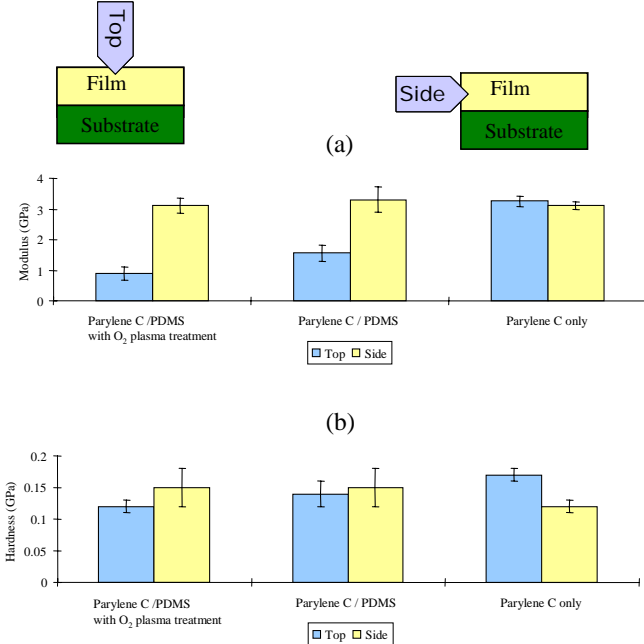
This decreasing behavior can be attributed to the same substrate effect mentioned above.

Fig. 5: Mechanical properties of Parylene coatings on different substrate conditions: (a) elastic modulus; (b) hardness.

In addition, the dynamic nanoindentation testing was done on the parylene coating deposited on the glass substrate. Figure 6 shows the results from the variation of modulus and hardness with indentation depth for different film thicknesses. As shown, the substrate effect was clearly shown on very thin parylene coatings (1.5-µm and 5-µm thick), where moduli were overestimated and increased with indentation depth due to a stiffer substrate beneath the parylene. Hardness values were also overestimated but less dependent upon the indentation depth. The thicker parylene coatings did not show this effect, and the values of modulus and hardness were close to the side indentation results.

Viscoelastic properties of the parylene-coated PDMS samples are shown in Fig. 7 over the indentation depth range. The parameter 'tan δ' represents for the damping capabilities of the materials. Due to the underlying PDMS, the storage modulus values (about 1-2.5 GPa) seemed to be lower than those in Fig. 6. These values are still much higher than those of PDMS by about 2-3 orders of magnitude. It indicates that the top parylene can effectively improve the surface properties of PDMS when coated. More analyses will be needed to better understand mechanical properties and associated mechanics of the bilayer structure. In addition, both storage and loss moduli decreased with increasing indentation depth.
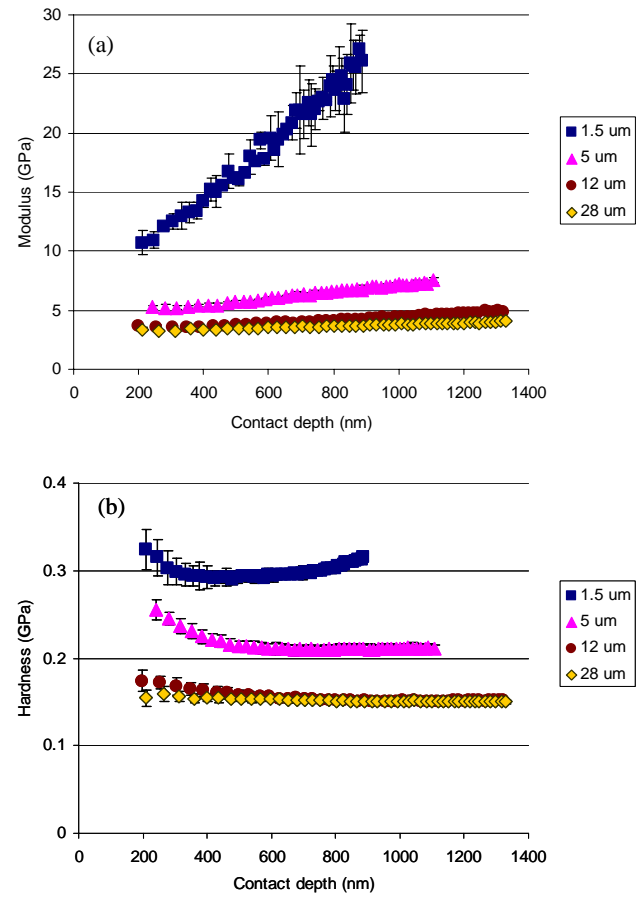

Fig. 6: Dynamic nanoindentation results of (a) modulus and (b) hardness of parylene C films as a function of indentation depth at various film thicknesses.
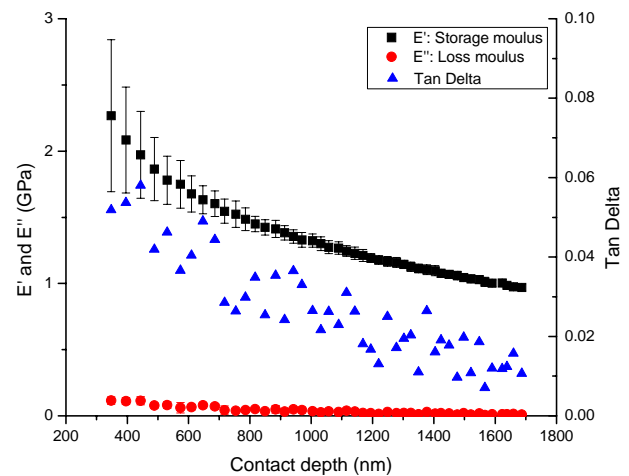

Fig. 7: Viscoelastic properties of the 12-µm thick parylene C coating deposited on PDMS. Dynamic nanoindentation was done with an AC load at 50 Hz.

CONCLUSION

In this study, we investigated processing and properties of the conformal parylene/PDMS coatings that have a potential use in packaging materials. Parylene processing via a vapor phase deposition was very reproducible, and its microstructure and performance seemed to be dependent upon the surface condition of the underlying substrate structure. The bubble-like features were also observed in the parylene film, and reduced by proper substrate surface conditions (e.g., PDMS with oxygen plasma treatment). More systematic study is necessary to have a fundamental understanding on this aspect.

Parylene has a hardness of about 130 MPa, and a modulus of 3.1 GPa, which is much harder and stiffer than PDMS, thus offering an effective means of enhancing surface properties of PDMS. Our preliminary studies indeed showed this potential of the bilayer structure. In particular, nanoindentation technique demonstrates its usefulness as a tool to characterize the polymer films provided that the underlying substrate effect can be well characterized. Future efforts will be directed at better understanding the mechanics of the bilayer structure in order to accurately assess its mechanical properties.

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