

Evaluation of the Adhesion Properties of Inorganic Materials with High Surface Energies

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With the aim of checking the validity of methods for characterizing the adhesion between inorganic materials with high surface energies, the properties of the adhesion between an inorganic material (indium tin oxide (ITO)) and model surfaces with various surface energies (Cl-, NH₂-, CH₃-, and CF₃-functionalized surfaces) were evaluated using atomic force microscopy (AFM) and the Johnson–Kendall–Roberts (JKR) apparatus. For this purpose, the AFM tip and the JKR lens were modified with ITO using radio frequency (rf) magnetron sputtering. The work of adhesion between the ITO coating and each model surface was estimated using AFM and the JKR apparatus and compared with the result obtained from contact angle measurements. The adhesion forces determined from the force–displacement curves (AFM) were found to agree with the predictions of the Derjaguin–Muller–Toporov (DMT) theory. The JKR equation used in the interpretation of the JKR experiments was modified by taking into account the differences between the surface and bulk moduli of the ITO-coated poly(dimethylsiloxane) (PDMS) lens. The ratio of the surface modulus to the bulk modulus we used in this modified JKR equation was obtained by determining the slope of the attracting part of the force–displacement curve. The values of the work of adhesion calculated using the modified JKR equation were also found to agree with the values obtained from contact angle measurements. We conclude that the two methods using AFM and the JKR apparatus can be used in the evaluation of the work of adhesion between inorganic materials with high surface energies such as metal and metal oxide surfaces.

Introduction

Metal and metal oxide multilayered thin films have been used in many electrical devices, such as laser diodes, light emitting devices, and thin film transistors.^{1–4} Several methods have been used to prepare metal and metal oxide films, such as direct current (dc) and radio frequency (rf) magnetron sputtering, ion beam sputtering, reactive evaporation, and pulsed laser deposition.^{5–8} The adhesion properties of these inorganic materials are crucial to the performance of electrical devices. A lower electrical resistivity was obtained for the materials with higher interfacial adhesion due to the higher mobility of carriers that undergo less interfacial scattering.⁹ According to the well-known empirical formalism of Gent and Schultz, the adhesion energy is made up of the intrinsic work of adhesion associated with the surface properties and the viscoelastic dissipation energy of the adherends that results from deformation of the materials.^{10,11} However,

in the case of inorganic materials, the viscoelastic dissipation term is negligible because they have extremely high moduli. Therefore, the intrinsic work of adhesion is the main contribution to the adhesion energy.

The work of adhesion is the decrease in the Gibbs free energy per unit area when an interface is formed between two surfaces, so the greater the interfacial attraction, the greater the work of adhesion.¹² It is commonly accepted that the geometric mean of the dispersion components of the surface energies can be used to determine the dispersion component of the work of adhesion. An analogous geometric mean rule for the polar component of the work of adhesion can be used to provide a relationship between the work of adhesion and the surface energy. Generally, the work of adhesion (W_a) for inert media can be expressed as follows:^{13–17}

$$W_a = 2(\gamma_1^p \gamma_2^p)^{1/2} + 2(\gamma_1^d \gamma_2^d)^{1/2} \quad (1)$$

where γ_1 and γ_2 are the surface energies of the samples and the superscripts d and p refer to the dispersion and polar (nondispersion) components of the surface energy, respectively.

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- (1) Hamberg, I.; Granqvist, C. G. *J. Appl. Phys.* **1986**, *60*, R123.
- (2) Aliyu, Y. H.; Morgan, D. V.; Thomas, H.; Bland, S. W. *Electron. Lett.* **1995**, *31*, 1691.
- (3) Meng, L. J.; Li, C. H.; Zhong, G. Z. *J. Lumin.* **1987**, *39*, 11.
- (4) Kobayashi, H.; Ishida, T.; Nakato, Y.; Tsubomura, H. *J. Appl. Phys.* **1991**, *69*, 1736.
- (5) Lee, B. H.; Kim, I. G.; Cho, S. W.; Lee, S. *Thin Solid Films* **1997**, *302*, 25.
- (6) Meng, L.; dos Santos, M. P. *Thin Solid Films* **1998**, *322*, 56.
- (7) Kim, D.; Han, Y.; Cho, J.; Koh, S. *Thin Solid Films* **2000**, *81*, 377.
- (8) Hambermeir, H. U. *Thin Solid Films* **1980**, *80*, 157.
- (9) Ohgi, T.; Sheng, H. Y.; Dong, Z. C.; Nejoh, H.; Fujita, D. *Appl. Phys. Lett.* **2001**, *79*, 2453.
- (10) Gent, A. N.; Shultz, J. *J. Adhes.* **1972**, *3*, 281.

(11) Andrews, E. H.; Kinloch, A. J. *Proc. R. Soc. London, Ser. A* **1973**, *332*, 385.

(12) Pocius, V. A. *Adhesion and Adhesive Technology*; Hanser/Gardner Publications: New York, 1997.

(13) Israelachvili, J. N. *Intermolecular and Surface Forces*, 2nd ed.; Academic Press: London, 1991.

(14) Owens, D. K. *J. Appl. Polym. Sci.* **1970**, *14*, 1725.

(15) Good, R. J. *J. Colloid Interface Sci.* **1977**, *59*, 398.

(16) Schultz, J.; Tsutsumi, K.; Donnet, J. D. *J. Colloid Interface Sci.* **1977**, *59*, 277.

(17) Van, O.; Carel, J. *Interfacial Forces in Aqueous Media*; Marcel Dekker: New York, 1994.

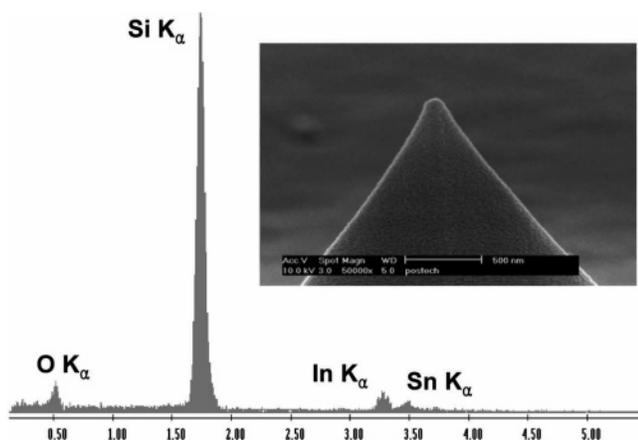


Figure 1. High resolution SEM images and EDAX spectra of the ITO-coated tip, showing its uniform coverage and the approximately spherical shape of the tip apex. The estimated radius of the tip is 71 nm.

However, this theoretical expression for the work of adhesion cannot be used for inorganic materials with high surface energies such as metal and metal oxide surfaces (400–4000 mJ/m^2) because contact angle measurements cannot be used to probe high energy surfaces that are wet by most liquids.¹³

In this paper, we describe a method for evaluating the adhesion properties of inorganic materials with high surface energies. To check the validity of this method, indium tin oxide (ITO), which is extensively used in electronic and optoelectronic device fabrication technologies, was deposited onto both an atomic force microscopy (AFM) tip and a poly(dimethylsiloxane) (PDMS) lens with an rf magnetron sputtering system, and the properties of the adhesion between ITO and various model surfaces with different surface energies were evaluated.

Experimental Section

Materials and Monolayer Preparation. 3-Chloropropyltriethoxysilane ($-\text{Cl}$), 3-aminopropyltriethoxysilane ($-\text{NH}_2$), octyltrichlorosilane ($-\text{CH}_3$), and trichloro(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)silane ($-\text{CF}_3$) were obtained from Aldrich and used as received. All the alkylsilanes as well as anhydrous toluene and anhydrous hexane were stored in a desiccator prior to use. Vacuum-dried reaction flasks were charged with anhydrous toluene and cleaned silicon wafers under argon. In the case of trichloro(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)silane, anhydrous hexane was used. The silicon wafers were cleaned in piranha solution (70 vol % H_2SO_4 + 30 vol % H_2O_2) for 30 min at 100 °C and then washed with distilled water. Solutions of alkylsilanes (10 mM) were then added to the flask and left to self-assemble on the wafers for 1 h under argon.

AFM Tip and Poly(dimethylsiloxane) Lens Modification. Indium tin oxide (ITO) was deposited onto the AFM tip and the PDMS lens at room temperature by using an rf magnetron sputtering system. The sputtering target was a 2 in. hot-pressed, sintered oxide ceramic (90 wt % In_2O_3 , 10 wt % SnO_2) supplied by Cerac Inc., U.S.A. The AFM tip and the PDMS lens were fixed directly above the target with a target-to-substrate distance of 10 cm. High purity argon gas was introduced through a mass flow controller after evacuating the vacuum chamber to $\sim 1 \times 10^{-6}$ Torr. The gas pressure was 1×10^{-2} Torr during deposition. The rf power was 60 W, and the deposition rate of ITO was ~ 10 nm/min. The uniform deposition of ITO was confirmed using scanning electron microscopy (SEM) and an energy dispersive analysis with X-ray spectroscopy (EDAX). The radius of curvature of the ITO-coated AFM tip was obtained from SEM (≈ 71 nm). The error in this measurement was estimated by drawing the minimum and maximum possible arc radii that coincided with the tip. Figure 1 shows the SEM image and the EDAX spectra

of the ITO-coated AFM tip. ITO was also found to be uniformly deposited on the PDMS lens, with a thickness of ≈ 10 nm.

Force–Displacement Curve Measurement. Force–displacement curves (f – d curves) for the interaction of the ITO-coated AFM tip with model surfaces with various functional groups (Cl , NH_2 , CH_3 , and CF_3) were obtained with an atomic force microscope (AutoProbe CP Research, Park Scientific Co.). The f – d curves were obtained by recording the AFM cantilever deflection caused by the vertical movement of the AFM tip. More than 10 f – d curves were obtained at each location through repeated tip approach/retract cycles, and the measurements were also repeated at more than 10 locations for each sample. The frequency of the approach/retract cycle, 1 Hz, was chosen so as to minimize the noise fluctuation in each f – d curve. The maximum loading force (1 nN) was kept constant for all f – d measurements, and sequential f – d curves were collected at 1 min intervals. However, in the case of the evaluation of the multiplying factor for use in the modified Johnson–Kendall–Roberts (JKR) equation, a bare silicon tip (spring constant, ~ 1.5 N/m) was used and the maximum loading force was 5 nN. These measurements were carried out under a nitrogen atmosphere to minimize uncertainties arising from capillary forces (relative humidity, 5–10%). To determine the absolute force value, the normal spring constant of the cantilever used in the experiment was calibrated with a nondestructive method described by Hutter and Bechhoeffer.¹⁸ An ITO-coated AFM tip with a spring constant of ~ 2.09 N/m was used.

Johnson–Kendall–Roberts Method. The adhesion energy was measured using a homemade Johnson–Kendall–Roberts (JKR) apparatus. Briefly, the instrument consists of the following main components: an electrobalance (to record the contact force), an optical microscope (to monitor the contact radius), and a manipulator (to control the probe). The JKR apparatus is placed on a vibration-isolation table and housed within a humidity-controlled chamber. All JKR experiments were performed under a nitrogen atmosphere, with a relative humidity between 5 and 10%. A cross-linked poly(dimethylsiloxane) (PDMS) (Sylgard 184, Dow Corning) hemispherical lens (diameter, ≈ 1 mm) was fabricated according to literature methods. The cross-linked PDMS lens was modified with ITO using an rf magnetron sputtering system. From the point of initial contact, the probe lens was lowered 6 μm with 10 steps of compression (0.6 μm per step), and the resulting load (P) and contact radius (a) were monitored. For each step, the surfaces were left in contact for 2 min to obtain equilibrium conditions.

Results and Discussion

A. Atomic Force Microscopy Experiments (Force–Displacement Curve). The adhesion forces between the ITO-coated AFM tip and model surfaces with various surface energies (Cl , NH_2 , CH_3 , and CF_3) were determined from the force–displacement curves. The f – d curves were obtained as follows.¹⁹ First, when the cantilever approaches the sample surface, there is typically no deflection in the cantilever and zero force is recorded. Second, the tip makes contact with the surface and pushes against the surface. The cantilever is bent up with the applied force. Finally, the tip is withdrawn from the surface. The cantilever is bent down until the tip reaches a distance at which the contact between the tip and the sample becomes broken. Then, the cantilever deflection reverts to its original condition in the noncontact region. The hysteresis in the force–displacement curve corresponds to the adhesion between the tip and the sample surface. All measurements were carried out under a nitrogen atmosphere rather than in solution so that the conditions were similar to those found in industrial systems.

Representative force–displacement curves for the interactions of the ITO-coated AFM tip with the model

(18) Hutter, J. L.; Bechhoeffer, J. *Rev. Sci. Instrum.* **1993**, *64*, 1868.

(19) Beach, E. R.; Tormoen, G. W.; Drelich, J.; Han, R. *J. Colloid Interface Sci.* **2002**, *247*, 84.

Table 1. Summary of Results for the Adhesion Experiments^a

					work of adhesion (W_a , mJ/m ²)			
	γ (mJ/m ²)	γ^p (mJ/m ²)	γ^d (mJ/m ²)	contact angle measurement	AFM		JKR	
					JKR theory	DMT theory	W_a^* (before correction)	W_a (after correction)
Cl	52.3	20.7	31.6	93.3	131.5 ± 31.8	98.6 ± 23.9	30.5 ± 0.3	91.5 ± 0.9
NH ₂	43.8	6.5	37.3	87.1	115.8 ± 44.5	86.8 ± 33.4	26.6 ± 1.5	79.8 ± 4.5
CH ₃	25.8	0.1	25.7	62.0	83.7 ± 21.2	62.8 ± 15.9	23.3 ± 2.2	69.9 ± 6.6
CF ₃	14.6	1.0	13.6	49.4	77.2 ± 25.4	57.9 ± 19.1	15.5 ± 0.3	46.5 ± 0.9

^a γ is the surface energy of the samples, and the superscripts d and p refer to the dispersion and polar (nondispersion) components of the surface energy, respectively.

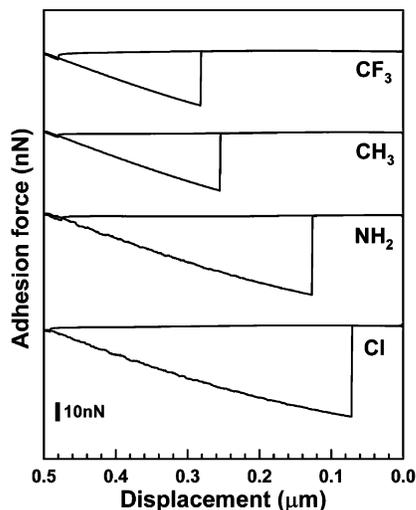


Figure 2. Representative force–displacement curves for the interaction of the ITO-coated tip with the model surfaces with various surface functional groups. All data were obtained under a nitrogen atmosphere.

surfaces with various surface energies are shown in Figure 2. The lowest adhesion force was observed for the CF₃-modified surface, and the highest adhesion force was found for the Cl-modified surface. The mean value of the adhesion forces was found to increase as the surface energy increased; that is, a higher surface energy results in a larger adhesion force.

The adhesion force determined with AFM can be related to the work of adhesion using contact mechanics for the elastic contact of solid surfaces. There are two readily tractable approaches: the Johnson–Kendall–Roberts (JKR) theory and the Derjaguin–Muller–Toporov (DMT) theory.^{20–23} Both models are based on an earlier analysis by Hertz, who considered two elastic bodies in contact under an external load but ignored the attractive interparticle forces.²⁴ The JKR theory was developed to describe relatively high adhesive forces and soft materials.²⁰ It neglects long range forces outside the contact area and considers only short range interfacial forces inside the contact region. A finite contact area exists upon rupture. It is assumed that the AFM tip apex that comes into contact with the sample during force measurements is spherical. Then, the pull-off force required to separate a spherical tip of radius R from a planar surface is directly

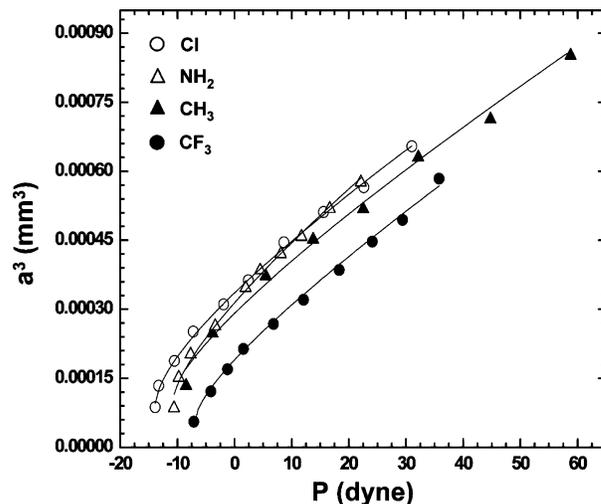


Figure 3. Contact radius (a) vs applied normal load (P) data for the interaction of the ITO-coated PDMS lens with the model surfaces with various surface energies.

proportional to the work of adhesion (W_a):

$$F_{ad} = \frac{3}{2}\pi RW_a \quad (2)$$

For hard surfaces and weak adhesion, the DMT theory provides a better approximation.²¹ It assumes that interfacial forces act only over a finite range and that there is no contact between the tip and the sample upon rupture. For the DMT theory, the adhesion force is related to the work of adhesion by

$$F_{ad} = 2\pi RW_a \quad (3)$$

The work of adhesion was estimated using the JKR and DMT theories from the experimentally measured adhesion forces for each system and was compared to the work of adhesion obtained from contact angle measurements (Table 1). In the contact angle measurements, two liquids (distilled water and diiodomethane) were used. The surface energy determined from the contact angle measurements is directly correlated to the thermodynamic work of adhesion (W_a), as shown in eq 1. The surface energy and work of adhesion determined from the contact angle measurements are shown for each surface in Table 1. Figure 5 shows the work of adhesion for each surface obtained from the contact angle measurements and the experimental values (JKR and DMT theory). The mean value of the work of adhesion increases almost linearly as the surface energy increases. There is good agreement between the experimental values determined using the DMT theory and the values calculated from the contact angles. From these results, it can be concluded that the DMT theory provides a reasonably good approximation

(20) Johnson, K. L.; Kendall, K.; Roberts, A. D. *Proc. R. Soc. London, Ser. A* **1971**, *324*, 301.

(21) Derjaguin, B. V.; Muller, V. M.; Toporov, Yu. *J. Colloid Interface Sci.* **1975**, *53*, 314.

(22) Muller, V. M.; Yushchenko, V. S.; Derjaguin, B. V. *J. Colloid Interface Sci.* **1980**, *77*, 91.

(23) Muller, V. M.; Yushchenko, V. S.; Derjaguin, B. V. *J. Colloid Interface Sci.* **1983**, *92*, 92.

(24) Hertz, H.; Reine, *J. Angew. Math.* **1881**, *92*, 156.

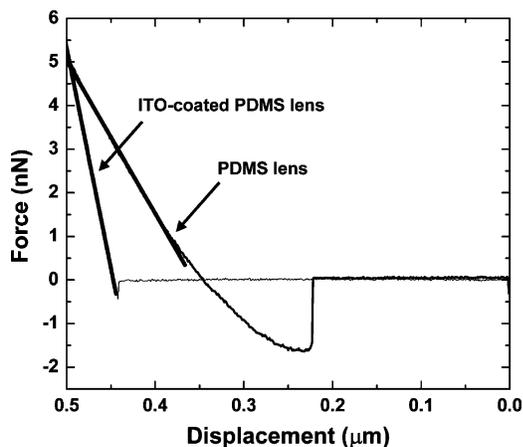


Figure 4. Loading parts of the force–displacement curves for the interaction of the silicon tip and the PDMS lenses (bare PDMS lens and ITO-coated PDMS lens).

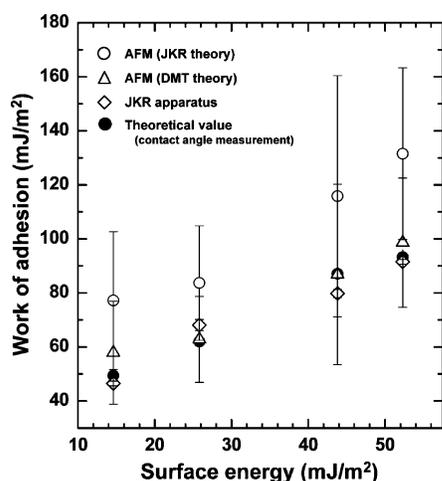


Figure 5. Work of adhesion determined from contact angle measurements, from AFM (JKR theory and DMT theory), and with the JKR apparatus as a function of the surface energy.

for the contact between the ITO-coated AFM tip and model surfaces with various surface energies.

To check the validity of this approach, we calculated the adhesion force between an ITO-coated AFM tip and an ITO thin film.^{25–27} The surface energy of ITO thin films as determined from contact angle measurements is 43.5 mJ/m². For interactions between two identical surfaces, W_a is equal to twice the value of the surface energy. According to the DMT theory, the adhesion force calculated using this value and the radius of the AFM tip (~ 71 nm) is 38.8 nN. This value agrees with the experimentally determined value (40.9 ± 8.6 nN). These results also demonstrate that the DMT approach provides a reasonable means of interpreting our nanometer-scale measurements of the adhesion between an ITO-coated AFM tip and model surfaces with various functional groups.

However, it is difficult to resolve the discrepancy between the JKR and DMT theories for the predicted pull-off force because of the width of the adhesion force distribution and errors in determination of the normal spring constant.^{28,29} Further, the calculation of the adhe-

sion energy is strongly dependent on the accuracy of the measurement of the tip radius because, as can be seen in eqs 2 and 3, the adhesion energy is a function of the tip radius, assuming that the pull-off force derives purely from the interfacial force between the two materials.

B. Johnson–Kendall–Roberts Experiments. A technique using a JKR apparatus was also employed in this study. The JKR apparatus uses a transparent and flexible material (PDMS) in the shape of a hemisphere as a probe.^{30–32} Generally, the radius of the PDMS lens is ~ 1 mm and the observed contact radius is often larger than ~ 50 μm . Therefore, more accurate values of the adhesion energy are obtained for larger-scale experiments with this apparatus than in the case of AFM experiments. A PDMS lens coated with ITO ($t \sim 10$ nm) was brought into contact with the model surfaces.

Our system is different from conventional JKR experiments using a bare PDMS or polymer-modified PDMS lens because an inorganic rigid layer (ITO) is deposited onto the PDMS lens.³³ The bulk modulus (K_B) and the surface modulus (K_S) of the ITO-coated PDMS lens are expected to be different. According to Hertz, initial increases in the contact area are governed by the bulk modulus (K_B).²⁴ Further increases in contact area due to interfacial attraction are governed by the surface modulus (K_S) because interaction forces are effective only at the interface between the two contacting materials.²⁰ Therefore, the JKR equation needs to be modified by separating the contributions due to the bulk modulus (K_B) and the surface modulus (K_S) of the ITO-coated PDMS lens as follows:

$$\alpha^3 = \frac{R}{K_B} [P + 3\pi W_a^* R + (6\pi W_a^* R P + (3\pi W_a^* R)^2)^{1/2}] \quad (4)$$

where

$$W_a = \frac{K_S}{K_B} W_a^*$$

$$f = \frac{K_S}{K_B}$$

W_a^* is the work of adhesion before correction, and W_a is the work of adhesion after correction. f is the multiplying factor, which is the ratio of the surface modulus to the bulk modulus.

Figure 3 shows representative α^3 – P curves for the model surfaces. The experimental data were fitted with eq 4 to evaluate W_a^* and K_B . These values of W_a^* (Table 1) were found to be quite small compared to the theoretical values obtained from the contact angle measurements. One difficulty is how to evaluate the multiplying factor (f) experimentally. At first sight, it seems that the surface modulus of the ITO-coated PDMS lens (K_S) is the modulus of ITO. However, the outer rigid layer is supported by flexible material, so the surface modulus of the ITO-coated PDMS lens (K_S) is in fact much lower than the modulus of the outer rigid layer alone. The force–displacement curve (AFM) was used to evaluate the multiplying factor.

(25) van der Vegte, E. W.; Hadziioannou, G. *Langmuir* **1997**, *13*, 4357.

(26) Noy, A.; Frisbie, C. D.; Rozsnyay, L. F.; Wrighton, M. S.; Lieber, C. M. *J. Am. Chem. Soc.* **1995**, *117*, 7943.

(27) Tsukruk, V. V.; Bliznyuk, V. N. *Langmuir* **1998**, *14*, 446.

(28) Vezenov, D. V.; Zhuk, A. V.; Whitesides, G. M.; Lieber, C. M. *J. Am. Chem. Soc.* **2002**, *124*, 10578.

(29) Thomas, R. C.; Houston, J. E.; Crooks, R. M.; Kim, T.; Michalske, T. A. *J. Am. Chem. Soc.* **1995**, *117*, 3830.

(30) Chaudhury, M. K.; Whitesides, G. M. *Science* **1992**, *255*, 1239.

(31) Ahn, D.; Shull, K. R. *Macromolecules* **1996**, *29*, 4381.

(32) Lee, D. H.; Kim, D.; Oh, T.; Cho, K. *Langmuir* **2004**, *20*, 8124.

(33) Efimenko, K.; Wallace, W. E.; Genzer, J. *J. Colloid Interface Sci.* **2002**, *254*, 306.

The slope of the attracting part of the force–displacement curve provides information about the modulus of the sample.^{34,35} The attracting parts of the f – d curves for the bare PDMS lens and ITO-coated PDMS lens are presented in Figure 4. The slope of the f – d curve for the ITO-coated PDMS lens is higher than that for the bare PDMS lens by a factor of 3. This means that the surface modulus (K_S) of the ITO-coated PDMS lens is ~ 3 times larger than the bulk modulus (K_B). The multiplying factor (f) is ~ 3 . Therefore, we corrected the previously obtained W_a^* values by this factor. It can be seen that the values of the corrected work of adhesion are quite close to the theoretical values, as shown in Table 1 and Figure 5. These results support our evaluation of the multiplying factor.

In this work, the outer rigid layer can be considered to be very thin and make no contribution to the bulk modulus. However, the effect of both the ITO layer and its roughness should be taken into account. A more systematic study that takes into account the effects of layer thickness and roughness, as well as the mechanical properties of the outer layer, is ongoing.

Summary and Conclusions

We propose the methods using an AFM tip and a JKR lens modified by inorganic materials to evaluate the adhesion properties between inorganic materials with high surface energies. The AFM tip, PDMS lens, and substrate can be modified by various methods such as dc and rf magnetron sputtering, ion beam sputtering, reactive evaporation, and pulsed laser deposition.

(34) Bliznyuk, V. N.; Assender, H. E.; Briggs, A. D. *Macromolecules* **2002**, *35*, 6613.

(35) Tsui, O. K. C.; Wang, X. P.; Jacob, Y. L. Ho.; Ng, T. K.; Xiao, X. *Macromolecules* **2000**, *33*, 4198.

To check the validity of this method, the adhesion properties of indium tin oxide (ITO) and model surfaces with various surface energies (Cl-, NH₂-, CH₃-, and CF₃-terminated self-assembled monolayers (SAMs)) were investigated using the ITO-coated AFM tip and JKR lens. In the case of the method using AFM, we found that the Derjaguin–Muller–Toporov (DMT) approach provides a reasonable means for the interpretation of the nanometer-scale measurements of the adhesion between the ITO-coated tip and the model surfaces. However, the work of adhesion obtained using the JKR apparatus is about one-third of that obtained from contact angle measurements. This effect was taken into account by using a multiplying factor that is the ratio of the surface modulus to the bulk modulus of the ITO-coated PDMS lens. This factor can be obtained from the slope of the attracting part of the force–displacement curve.

These AFM and JKR methods using probes modified with inorganic materials can be applied to the evaluation of the work of adhesion between inorganic materials with high surface energies such as metal and metal oxide surfaces.

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Supporting Information Available: Discussion on the modification of the JKR equation for an ITO-coated PDMS lens. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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