Processing Dependent Behavior of Soft Imprint Lithography on the 1–10-nm Scale

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Abstract—This paper examines aspects of a soft nanoimprint lithography technique for operation at resolutions that approach the 1-nm regime. Systematic studies using polymer molds made with single walled carbon nanotubes (diameters between 0.5 and 5 nm) and high-resolution electron beam patterned layers of hydrogen silsesquioxane (line widths and heights ~ 10 and 20 nm, respectively) as templates reveal a dependence of the resolution limits on the polymer processing conditions. In particular, using a single choice of polymers for the molds and the molded materials, imprint results show that the conditions for spin casting and curing the polymers determine, to a large degree, the resolution and replication fidelity that can be achieved. Optimized procedures enable imprinted polymer surfaces that have a root mean squared surface roughness of ~ 0.26 nm or lower and a resolution as high as ~ 1 nm. These characteristics are significantly better than previous results obtained using these same polymers with unoptimized conditions. A diversity of molded polymers, including Bisphenol-F epoxy resin, polyacrylic acid, and polyurethane, show similar high-fidelity imprinting capabilities. Different procedures enable accurate relief replication for features with modest aspect ratios and dimensions of \sim 10 nm. The results indicate that choice of processing conditions is, in addition to materials selections, extremely important in achieving high-fidelity soft nanoimprint lithography in the 1–10-nm regime.

Index Terms—Imprint lithography, next generation lithography, poly(dimethylsiloxane) (PDMS), polymer physics, replica molding.

I. INTRODUCTION

PROGRESS IN semiconductor technology depends on continued improvements in capabilities for patterning structures with nanometer dimensions and, ultimately, in techniques for manufacturing them at low costs. The wavelengths

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of photons limit the minimum feature sizes that can be produced by conventional (i.e., those that do not use near field, plasmonic, or other effects) photolithographic techniques. Next generation lithography (NGL) methods [1]-[5], which do not rely on traditional optics, may be required for patterning beyond this level of resolution. Among these NGL techniques, ultraviolet nanoimprint lithography (UV-NIL) is believed by some to represent a promising technique with potential for low-cost, high-throughput, and high-resolution operation [6]-[8]. A soft UV-NIL that exploits polymer molds, made by casting and curing materials such as poly(dimethylsiloxane) (PDMS) against templates, is of wide and growing interest, especially for applications (e.g., nanoelectronics, flexible electronics, and biotechnology) that lie outside of conventional microelectronics. In this procedure, which represents a form of soft lithography often referred to as replica molding, the molds generate relief structures in films of a UV curable prepolymer.

The polymers for the molds as well as those for the molded material influence the resolution. Both polymers, in their liquid, uncured, and uncrosslinked states, must be able to come into perfect conformal contact with the interface (with the SWNT template or with the mold) to establish an atomically accurate replica of the relief structures or the flat surfaces on a template or mold. The conformation that a polymer adopts mainly depends on the flexibility of the chains and the strength of the interactions between the monomers, oligomers, or uncrosslinked polymers and the surroundings [14]. The linear backbone and low-energy barriers to torsional motion in PDMS make it one of the most flexible polymers. The inset of Fig. 1 illustrates a possible configuration (determined with the software Cerius 2) for conformal contact between PDMS and a SWNT. Once in conformal contact, the polymer must also be able, in its cured state, to retain the molded shape. Although cured PDMS has the attractive features of mechanical elasticity and physical toughness, its glass transition temperature is far below room temperature. As a result, the polymer segments between crosslinks are flexible and may have difficulty in retaining molded shapes that have length scales smaller than the average distance between crosslinks. Our previous work suggested, in fact, that the density of the crosslinks is an important chemical characteristic of a polymer that can influence the achievable resolution [18].

This paper illustrates a different aspect of soft nanoimprint lithography that is also critically important to the fidelity and resolution of the process. In particular, data show that processing details not directly related to materials choices can strongly influence the operation of soft nanoimprint lithography, especially at resolutions between 1 and 10 nm. For a



Fig. 1. (Left) Schematic illustration of steps for soft nanoimprint lithography process that uses single-walled carbon nanotubes as templates and ultraviolet curable polymers to investigate resolution in 1-nm regime. (Right) Illustration of steps for molding structures with lateral and vertical dimensions in 10- and 20-nm regime, respectively.

given set of materials for the molds and the molded films, the achievable resolution can span a wide range, depending on the processing conditions. To illustrate these effects, we performed systematic soft imprint lithography of patterns with critical dimensions in the 1-10-nm range. For features smaller than \sim 5 nm, single-walled carbon nanotubes served as templates to generate the PDMS molds [18]. For larger geometries, we used patterns of hydrogen silsesquioxane (HSQ) defined with advanced forms of direct write electron beam lithography. We observed generally that processing procedures, such as speeds for spin casting and conditions for curing, influence the surface roughness in nominally flat regions of the imprinted patterns and, further, that low roughness enables high resolution in replication of lateral feature dimensions. Accurate replication of feature heights relies critically on processing conditions (which are sometimes different than those that lead to high resolution) that facilitate polymer flow. Systematic studies reveal sets of conditions that enable \sim 1-nm resolution and accurate relief replication for nearly 2:1 aspect ratio features with dimensions between 3 and 20 nm, using several different molded polymers. These results represent considerable improvements over those previously achieved with the same set of materials [18].

II. EXPERIMENTAL METHODS

Fig. 1 shows the two sets of procedures used for the SWNT and HSQ molding experiments. The templates in both cases were first exposed to a fluorinated silane vapor to create a nonstick surface in the exposed SiO_2 areas of the sample [11]. A high modulus poly(dimethylsiloxane) (h-PDMS) was then spin cast and cured on the template surface. A low modulus PDMS (s-PDMS) was poured onto top of this layer and then thermally cured [12], [13]. Peeling the h-PDMS/s-PDMS composite mold away from the template completed the process. The s-PDMS provides a soft, physically tough layer that makes the molds easy to handle. Flood exposing a layer of photocurable polymer, polyurethane (PU), on a silicon wafer to ultraviolet (UV) light passing through the PDMS mold cured the polymer into a solid form. In the final step, the PDMS mold was peeled back, leaving a replica of the relief on its surface. In the usual NIL process, a uniform etch back follows the molding. The studies presented here do not explore this part of the process.

Preparation of Templates: The molecular resolution (1-5 nm) templates consisted of randomly aligned individual SWNTs with diameters between 0.5 and 5 nm and a coverage of 1–10 tubes/ μ m² on SiO₂/Si wafers. The tubes were grown by methane-based chemical–vapor deposition (CVD) using a relatively high concentration of ferritin catalysts [9], [10]. A previous paper describes the details of template preparation [18]. Templates with features larger than 5 nm were produced by advanced forms of electron beam lithography [21]. In particular, negative-tone inorganic HSQ on silicon wafers was patterned by a JOEL (JBX-6000FS) electron beam lithography system with an energy of 50 kV. Templates fabricated in this

TABLE I FIVE DIFFERENT PROCEDURES FOR CASTING AND CURING h-PDMS FOR IMPRINT MOLDS AND SURFACE ROUGHNESS ASSOCIATED WITH MOLDED POLYMERS

Process	Spin Speed for h-	Pre-bake for	Thickness	RMS (nm)
	PDMS (rpm)	h-PDMS	of h-PDMS	surface
			(μm)	roughness
1	9000	RT, 24 hr	5	0.26
2	1000	65 °c, 4 min	10	0.34
3	9000	(1) 65 °c, 3 min (2) RT, 24 hr	5	0.33
4	9000	65 °c, 4 min	5	0.32
5	1000	RT, 24 hr	10	0.39

manner consisted of arrays of 10-nm-wide lines separated by 30 nm, with heights between 3 and 20 nm. Since the line is not uniform in height along its length, it is possible to observe the replication for aspect ratios between 0.3 and 2.

Investigation of Effect of Spin Speed on Surface Roughness of Imprinted PU: Liquid PU (NOA 73 from Norland Products; viscosity 130 cps) was spin cast onto silicon wafers at different spin speeds and imprinted by a flat PDMS mold derived from a bare fluorinated silicon surface using processes in Table I. The PU was completely cured at a dose of 70 J/cm² from a UV Hg lamp (350–380 nm). The surface roughness of the PU layers was then characterized by atomic force microscopy (AFM) using ultra-sharp tips (nanosensors) and identical measurement conditions. The vendor specification for the tip radius is ~2 nm. The images were collected in tapping mode with a 1-Hz-per-line scan rate and a scan range of $1 \times 1 \mu m$.

Investigation of Effect of Spin Speed and Curing Temperature on Surface Roughness of h-PDMS: Table I illustrates five procedures for making the h-PDMS layer of a composite mold, using a bare fluorinated silicon wafer as a template. The overall process parameters are the same as those described in [18], but some of the spin speed, curing temperatures, and times are different. After prebaking the h-PDMS, a layer of s-PDMS material was poured onto the top and cured for 2 h at 65 °C. PU layers (spin cast at 9000 r/min on a silicon wafer and UV cured at a dose of 70 J/cm²) were then imprinted by PDMS molds prepared using these procedures. AFM analysis determined the surface roughness of the PU in each case using the procedures described previously. (Direct AFM measurement of the PDMS element was not possible, due to the soft, tacky surface characteristic of elastomers such as PDMS.)

Molecular Scale Soft Nanoimprint Lithography: We followed the process that minimized the surface roughness on the PU: 1) treat the SWNT template surface with silane; 2) spin cast the h-PDMS on the template at 9000 r/min; 3) allow curing to proceed at room temperature for 24 h; 4) pour on the s-PDMS and cure at 65 °C for 2 h; 5) separate the template and PDMS mold; 6) spin cast PU on a silicon wafer at 9000 r/min; 7) place a PDMS mold on the PU and flood expose with UV light at a dose of 70 J/cm²; and 8) peel back the PDMS mold from PU surface.

Molecular Simulation of PDMS Conformability to SWNT: Simulations were conducted with the commercial polymer modeling program, Cerius 2. At the beginning, a tube was introduced and defined as the rigid body. Monomer units of PDMS were added sequentially to form a linked PDMS polymer structure close to the SWNT. After each addition of each monomer, the system energy was minimized under a consistent force field (pcff).

Soft Nanoimprint Lithography for Modest Aspect Ratio Fea*tures of HSQ at* ~ 10 nm: Two procedures were attempted. The first used a processing sequence similar to that for the SWNT templates. After the HSQ template was silanized, h-PDMS was spin cast on it at 3000 r/min. They were cured at 65 °C for 3 min. Then, s-PDMS was poured on and put in 65 °C again for 2 h. After the composite PDMS mold was ready, it was peeled back from the HSQ template. It was then placed on the liquid PU that was drop cast on silicon wafer. The PU under the PDMS mold was cured by UV light exposure at room temperature. The curing is done in atmosphere. After the PDMS mold was peeled back from the PU, a height loss of the replica was observed. The second, which was observed to improve the accuracy of the height replication, began by placing the PDMS mold with its structured side up and the PU cast directly on top. This structure was then moved into a vacuum chamber and heated at 80 °C for 1 h. Placing the PU coated PDMS mold against a silicon wafer, curing the PU with UV light, and then peeling away the PDMS mold completed the process.

III. RESULTS AND DISCUSSIONS

We begin by describing the roughness of imprinted films, because we find that resolution in the 1-5-nm regime depends critically on the ability to generate smooth imprinted films in the unpatterned areas. Fig. 2(a) shows the dependence of the surface roughness of imprinted PU on spin speed, as determined by the root mean squared (rms) amplitude measured by tapping mode AFM. The dark curve illustrates the roughness of PU imprinted by a flat PDMS mold prepared by process 1 in Table I. The data indicate a clear trend to lower roughness with increasing spin speed. Fig. 2(b)-(e) shows the corresponding AFM images. We observed little variation in the surface topography across the 2×2 cm area of the samples. The minimum roughness observed consistently was ~ 0.26 nm, obtained by spin casting the PU prepolymer at 9000 r/min. The same trend of decreasing surface roughness with increasing spin speed was also observed with PDMS molds prepared by other processes in Table I. For example, the surface roughness of the PU imprinted by PDMS molds prepared by process 2 is 0.69, 0.48, 0.4, and 0.34 nm at spin speeds of 0, 3000, 6000 and 9000 r/min, respectively, as illustrated by the light curve in Fig. 2(a). The PU thicknesses for spin speeds of 9000, 6000, and 3000 r/min are $\sim 1, 1.3$, and $6 \,\mu$ m, respectively, measured after curing under PDMS molds. The thickness for the drop cast PU depends on how hard the PDMS mold was pressed against it during the imprinting; a typical thickness was ~ 1 mm. (We did not observe any systematic change in roughness with UV exposure dose, provided that the dose was sufficient $(>3 \text{ J/cm}^2)$ to induce complete curing.) Possible causes of the dependence of surface roughness on spin speed include changes in the molecular weight distribution or chemical composition of the remaining PU (whose



Fig. 2. (a) Surface roughness for imprinted films of photocurable polyurethane (PU). Dark and light curves represent PU imprinted by PDMS molds prepared by processes 1 and 2 in Table I. (b)–(e). Tapping mode AFM images of PU surface (imprinted by PDMS mold prepared by process 1 in Table I) which were spin cast at different speeds.

detailed chemical composition is not available from the vendor) or changes in the molecular shape, the degree of ordering or cystallinity, and/or the chain entanglement [15]-[17]. To explore these possibilities, we performed prism coupling measurements of the in-plane and out-of-plane indexes of refraction, infrared absorption spectroscopy on films with different thicknesses, X-ray diffraction, and differential scanning calorimetry (DSC). None of these experiments revealed any significant chemical or structural differences in any of the samples. For example, the results of the polarized infrared measurements reveal no dependence of the absorption features on processing conditions. The prism coupling measurements show insignificant differences between the in- and out-of-plane index of refraction, suggesting an absence of structural ordering that could potentially be induced by the spin casting. Wide angle X-ray diffraction shows a similar degree of crystallinity in films coated at 3000, 6000, and 9000 r/min, with a somewhat lower crystallinity in the drop cast films. DSC traces do not reveal any difference in glass transition temperature. Thermally excited interfacial capillary waves provide one possible explanation that is consistent with this set of measurements. This type of effect, when it occurs between two immiscible polymers, can contribute to a broadening of the interface. In fact, the interface roughness, between certain polymers, is found to have a dependence on the film thickness due to the capillary waves [22], [23]. Additional work, such as detailed temperature dependent studies, is required to explore further this possibility.

We also investigated the influence of similar processing related conditions for the preparation of the PDMS stamps. In particular, sets of experiments were performed with different curing temperatures and spin speed deposition conditions for the h-PDMS. The fluorinated surfaces of bare silicon wafers served as the templates. Although it was difficult to obtain reliable AFM measurements from the low modulus surface of the PDMS itself, we could examine the roughness of layers of PU imprinted by the PDMS molds. The flat PDMS molded PU samples processed using the optimized high-spin speed deposition conditions described previously. Among the five PDMS molds studied in Table I, process 1 generated the smoothest imprinted PU surface, ~ 0.26 nm in roughness. In processes 2–5, the h-PDMS was either spin cast at low spin speeds or cured at elevated temperatures. The results suggest that elevated temperatures, which provide the polymer chains with significant mobility, lead to rough surfaces. Long curing times associated with low temperatures reduce the roughness, perhaps by providing the polymer chains with adequate time to relax and conform to the interfaces.

We performed molecular scale imprinting by use of SWNT templates and the best procedures for making and using the PDMS molds with PU. Fig. 3(a)-(c) shows AFM images $(10 \times 10 \ \mu m)$ of a SWNT template, the template after the mold generation process, and the imprinted PU surface. Fig. 3(b) shows that the process of generating the molds does not alter AFM observable features of the template (the curled tube that appears on the template after, but not before, mold generation was likely transported to the measured area during one of the processing or imaging steps). The entire surface of the template after use is largely clean and without observable polymeric residue. (At the high resolution that is possible with optimized conditions, it is possible to observe small amounts of residue in selected regions of the templates.) The image of the PU replica [Fig. 3(c)] shows high fidelity and a capability to replicate, at least partially, the smallest observable SWNTs-diameters slightly less than ~ 1 nm. This result is approximately two times better than our previously reported results. The SWNTs with sizes larger than 1 nm were all reproduced cleanly along their entire lengths. In particular, the relief structures associated with the 3.5-nm tubes were fully replicated without loss in height. It is important to note that the small difference between the heights of the SWNTs and the molded features, and especially the complete height recovery at 3.5 nm, in the optimized process is consistent with a small effect of the silane layer (used to prevent adhesion between the PDMS and the template during mold preparation), either due to incomplete coverage near the SWNTs or to a partial or fully horizontal orientation of the silane molecules after the PDMS is cast on the substrate [19], [20].





SWNT (0.9 nm) on the master and its replica. Fig. 4(c) shows the heights of the replicas versus those of the corresponding features on the template. The height was averaged out along a straight section of the tube that is usually about 200 nm long, as illustrated by the white dashed lines in the inset of Fig. 4(a) and (b). We note that the AFM measurements can characterize accurately only the heights of the replicated features. Their lateral dimensions are difficult to determine due to the effects of the nonnegligible tip radii of even the sharpest commercially available AFM tips. Deconvolving the effects of the tip shapes does not provide the reliable basis for analysis. Transmission electron microscopy of metal replicas, reported elsewhere for similar samples [18], suggests that the widths of the molded features are in the same range as their heights.

To explore further the operation of soft imprint lithography in the molecular regime, we molded other polymers such as Bisphenol-F epoxy resin (DER 354) and polyacrylic acid (PAA). Bisphenol-F epoxy resin was UV cured in a manner similar to that for the PU. The polyacrlyic acid, on the other hand, was imprinted while its solvent (methanol) evaporated. Fig. 5 shows results obtained using the *same* mold that produced the PU structures illustrated in Figs. 3 and 4. The resolution observed here is comparable to (or slightly worse than) that observed with PU. These results suggest a broad capability to pattern a range of polymers; they also demonstrate the ability



Fig. 3. Results of soft nanoimprint lithography with processing conditions optimized for operation in nanometer regime. (a) AFM image of $10 \times 10 \,\mu$ m region of SWNT template used to produce PDMS molds. Tube indicated by black arrow has a height of 3.5 nm; two tubes indicated by white arrows have heights of ~1 nm. (b) AFM image of same region on SWNT template collected after generating PDMS mold. (c) AFM image of corresponding region and layer of PU imprinted using PDMS mold.

The area in Fig. 3(c) delineated by the white square appears in Fig. 4(a) and (b). The high-resolution AFM images illustrate the

a <u>10</u>nm

<u>250nm</u>0nm b 10nm

250nm 0nm

С



DER 354

PAA

Fig. 5. AFM images of surfaces $(10 \times 10 \ \mu \text{m})$ of bisphenol-F epoxy resin (DER 354) and polyacrylic acid (PAA) that were imprinted against PDMS mold derived from SWNT template. Surface roughnesses of DER 354 and PAA produced by molding against flat PDMS molds are ~0.34 nm.



Fig. 6. (a) AFM image of lines of HSQ patterned by electron beam lithography. Inset shows SEM image. (b) AFM image of molded structure of PU obtained with procedures similar to those used in molecular scale molding. (c) AFM image of fully recovered replica with optimized process. (d) Graph of feature height as function of position evaluated along first left lines in (a) and (c). In (a)–(c), line cut at bottom of images illustrates height of resist lines evaluated along white lines in AFM images.

of a single mold to be used for multiple imprinting cycles, with little degradation even at the 1-nm resolution scale.

Although these optimized procedures enable previously unattainable levels of resolution, applying them to PDMS molds generated from HSQ templates highlights their limitations. Molds generated with these templates have relatively narrow (\sim 10 nm) and deep (\sim 20 nm) features of relief. Fig. 6(a) illustrates AFM images of the HSQ template with 10-nm-wide lines.

The inset is the scanning electron microscopy (SEM) image of the segment of the lines. Using the procedures that work well with the SWNT templates yields molded structures that accurately replicate the widths of the HSQ lines, but not their depths [Fig. 6(b)]. To accurately replicate the relief, it was necessary to heat the PU slightly in vacuum while it was in contact with the PDMS surface, using a procedure illustrated in Fig. 1. This heating reduces the viscosity of the PU and helps it fill the recessed regions in the PDMS mold. As described in the studies of molecular scale molding, however, the heating also increases the background roughness, which degrades the quality of the replica. Fig. 6(c) shows an AFM image of the replica generated with the heated process; the height is fully recovered. Measurements of height along the first left line of the template [Fig. 6(d)] and the molded structure in PU appear in Fig. 6(c).

IV. CONCLUSION

This paper demonstrates clearly that physical processing related variables, such as spin speed and curing conditions, can control (in addition to materials choices for the polymers) the resolution and replication fidelity that can be achieved in soft nanoimprint lithography, particularly when operated at molecular length scales. The data show, further, that the choice of processing conditions depends on the geometry of the features that are molded, thereby indicating the need to include process optimization as a key element, in addition to materials selection, in achieving desired results with this form of imprinting. For the case of features with aspect ratios near 1:1 and lateral dimensions less than 5 nm, optimized approaches extend the resolution of this technique into the single nanometer resolution regime, with a variety of polymers. This capability will likely find applications in nanoelectronics, ion transport, molecular sizing, or sorting and other areas that benefit from functionalized thin films patterned with molecular dimensions. Bulk molecular templating, known as molecular imprinting, [24], [25], has some similarities to the surface lithographic processes described here; as such, this type of templating might exhibit similar processing related effects.

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REFERENCES

- A. Kumar and G. M. Whitesides, "Features of gold having micrometer to centimeter dimensions can be formed through a combination of stamping with an elastomeric stamp and an alkanethiol "ink" followed by chemical etching," *Appl. Phys. Lett.*, vol. 63, pp. 2002–2004, 1993.
- [2] E. Kim, Y. Xia, X. M. Zhao, and G. M. Whitesides, "Solvent-assisted microcontact molding: A convenient method for fabricating three-dimensional structures on surfaces of polymers," *Adv. Mater.*, vol. 9, pp. 651–654, 1997.
- [3] Y. Xia *et al.*, "Replica molding using polymeric materials: A practical step toward nanomanufacturing," *Adv. Mater.*, vol. 9, pp. 147–149, 1997.
- [4] International Technology Roadmap for Semiconductors, 2003.
- [5] S. Y. Chou, C. Keimel, and J. Gu, "Ultrafast and direct imprint of nanostructures in silicon," *Nature*, vol. 417, pp. 835–837, 2002.
- [6] M. Colburn et al., Proc. SPIE, vol. 3997, pp. 453-457, 2000.
- [7] N. A. Melosh *et al.*, "Ultrahigh density nanowire lattices and circuits," *Science*, vol. 300, pp. 112–114, 2003.

- [8] M. D. Austin *et al.*, "Fabrication of 5 nm linewidth and 14 nm pitch features by nanoimprint lithography," *Appl. Phys. Lett.*, vol. 84, pp. 5299–5301, 2004.
- [9] Y. Li *et al.*, "Growth of single-walled carbon nanotubes from discrete catalytic nanoparticles of various sizes," *J. Phys. Chem.*, vol. 105, pp. 11424–11431, 2001.
- [10] W. Kim *et al.*, "Synthesis of ultralong and high percentage of semiconducting single-walled carbon nanotubes," *Nano Lett.*, vol. 2, pp. 703–708, 2002.
- [11] A. N. Parikh, D. L. Allara, I. B. Azouz, and F. Rondelez, "An intrinsic relationship between molecular structure in self-assembled *n*-alkylsiloxane monolayers," *J. Phys. Chem.*, vol. 98, pp. 7577–7590, 1994.
- [12] H. Schmid and B. Michel, "Siloxane polymers for high-resolution, highaccuracy soft lithography," *Macromolecules*, vol. 33, pp. 3042–3049, 2000.
- [13] T. W. Odom, J. Christopher, D. B. Wolfe, K. E. Paul, and G. M. Whitesides, "Improved pattern transfer in soft lithography using composite stamps," *Langmuir*, vol. 18, pp. 5314–5320, 2002.
- [14] M. Rubinstein and R. H. Colby, *Polymer Physics*. New York: Oxford Univ. Press, 2003.
- [15] S. Sills *et al.*, "Interfacial glass transition profiles in ultrathin, spin cast polymer films," *J. Chem. Phys.*, vol. 120, pp. 5334–5338, 2004.
- [16] Y. Shi, J. Liu, and Y. Yang, "Device performance and polymer morphology in polymer light emitting diodes: The control of thin film morphology and device quantum efficiency," *J. Appl. Phys.*, vol. 87, pp. 4254–4263, 2000.
- [17] F. Kremer, L. Hartmann, A. Serghei, P. Pouret, and L. Léger, "Molecular dynamics in thin grafted and spin-coated polymer layers," *Eur. Phys. J. E.*, vol. 12, pp. 139–142, 2003.
- [18] F. Hua et al., "Imprint lithography with molecular-scale resolution," Nano Lett., vol. 4, pp. 2467–2471, 2004.
- [19] A. Ulman, "Formation and structure of self-assembled monolayers," *Chem. Rev.*, vol. 96, pp. 1533–1554, 1996.
- [20] A. S. Duwez, U. Jonas, and H. Klein, "Influence of molecular arrangement in self-assembled monolayers on adhesion forces measured by chemical force microscopy," *ChemPhyschem.*, vol. 4, pp. 1107–1111, 2003.
- [21] M. Word, I. Adesida, and P. Berger, "Nanometer-period gratings in hydrogen silsesquioxane fabricated by electron beam lithography," J. Vac. Sci. Technol., vol. B21, pp. L12–L15, 2003.
- [22] M. Sferrazza, C. Xiao, R. A. L. Jones, D. G. Bucknall, J. Webster, and J. Penfold, "Evidence for capillary waves at immiscible polymer/polymer interfaces," *Phys. Rev. Lett.*, vol. 78, pp. 3693–3696, 1997.
- [23] C. M. Mate, M. F. Toney, and K. A. Leach, "Roughness of thin perfluoropolyether lubricant films: Influence on disk drive technology," *IEEE Trans. Magn.*, vol. 37, no. 3, pp. 1821–1823, May 2001.
- [24] G. Wulff, "Enzyme-like catalysis by molecularly imprinted polymers," *Chem. Rev.*, vol. 102, pp. 1–28, 2002.
- [25] A. Katz and M. E. Davis, "Molecular imprinting of bulk, microporous silica," *Nature*, vol. 403, pp. 286–289, 2000.



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