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Device Fabrication by Easy Soft Imprint Nano-Lithography

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A new robust and exceptionally simple procedure for soft nano-imprint lithography (Soft-NIL) is described, which provides easy access to nanoscale patterns of a host of active materials on a Si/SiO$_x$ surface. Partial curing of a thiol-ene based UV cross-linkable resin (<1 μm) for 30−40 s prior to imprinting resulted in sufficient buildup of resin molecular weight to prevent its absorption into polydimethylsiloxane molds yet maintain a low enough viscosity to allow for rapid molding of nanoscale features during the subsequent imprint-and-cure stage of the process. Imprinted features were easily transferred to the underlying substrate by traditional reactive ion etching and lift-off processes. Easy soft imprint nanolithography (ESINL) permitted the use of untreated PDMS molds for replicating patterns in gold, nickel, and complex aluminum capped silicon structures. ESINL was used to fabricate organic field effect transistors (poly(3,3‴-didodecylquaterthiophene, $W/L = 204$, $\mu_{\mathrm{sat}} = 6.0 \times 10^{-3}$ cm^2/(V·s)), demonstrating the first use of a soft *imprint* lithographic process to make such devices.

Introduction

Nanoimprint lithography (NIL) has been embraced by a number of users as a practical and cost-effective means for patterning surfaces, and an extensive body of work compiled thus far on NIL has shown its usefulness in producing nanoscale devices and topological platforms for various surface chemistries.[1–3] While thermal-NIL and UV-NIL are effective, they tend to require a special equipment to apply heat and/or pressure during the imprint,[4] although the cost of this equipment is a fraction of the expense of a photolithography fabrication facility. In many NIL techniques the ability to pattern large areas is hindered by the nonconformal contact of two rigid surfaces. Reliable patterns over large areas with even residual layers can now be achieved by techniques such as Step and Flash Imprint Lithography (S-FIL), but sophisticated equipment and expensive quartz molds are required.[5] Accordingly, barriers remain for users who wish to utilize NIL but are limited in resources or lack access to state-of-the-art fabrication facilities.

So called soft-lithographic patterning approaches have attracted a great deal of attention due to their simplicity, reliance on conformal soft image transfer materials such as polydimethylsiloxane (PDMS), and effectiveness in patterning large areas. [6–8] A number of variants of soft lithography have been developed to pattern metallic structures, most notable of which are nanotransfer (nTP)[9] and microcontact printing (μCP)[10–12] which both rely on thiols, presumably limiting them to the patterning of gold or other noble metals. Furthermore, the patterning of specific materials can be complicated by interaction of the material with the PDMS stamp. Copper, for example, has been shown to absorb siloxane oligomers and aluminum, which requires careful application of a release monolayer and water adhesion layer.[13,14] In particular, μCP can suffer from limited fidelity and lateral resolution due to thiol mobility on the metal coated substrate after transfer from the mold surface and is hampered by the need for caustic wet chemistry to etch through a masked metallic film which contributes to loss of lateral resolution due to the isotropic etch profiles.[15,16] Also, while nTP can be accomplished without employing thiols it still requires considerable pressure and heating of the

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substrate to obtain effective transfer[17] and the metal layer must be carefully deposited on the PDMS surface prior to each imprint, a potentially time-consuming and costly factor.

Soft-nanoimprint lithography (Soft-NIL) is a promising alternative nanopatterning approach where PDMS molds are used to imprint UV curable resists[16,18–21] or to mold polymer films by capillary force.[22] Soft-NIL is remarkable in its ability to utilize PDMS to produce consistent imprints of large areas, an attribute due in part to the low modulus ($\sim$2−3 MPa)[23–25] and low surface energy (20 mJ/m^2)[26,27] of PDMS. These advantageous properties allow a high degree of conformal contact between the PDMS mold and substrate regardless of surface irregularities. It is important to note the distinction between normal soft lithography where pattern size is generally above 1 μm and Soft-NIL where successful patterning of submicrometer features is the desired goal.

Despite the many successful demonstrations of imprinting into the surface of various resists by Soft-NIL, it is important to note that there is a dearth of reports of its use for true lithographic pattern transfer to fabricate useful submicrometer structures, and only one report of successful pattern transfer exists which involved chemical modification of the PDMS mold surface.[28] With the exception of capillary force lithography, which requires imprint times on the order of 1 day,[22,29] there are no reports of using the imprinted surfaces as etch (wet or dry) or lift-off masks in a true submicrometer lithographic fabrication process which is necessary for the conversion of imprinted resin features to useful materials such as gold for device electrodes.

Many of the limitations of Soft-NIL stem from the high permeability of organic liquids in PDMS.[30,31] Consequently, imprinting with PDMS has dictated the use of thick resist films such that the amount of material absorbed by the mold does not negate pattern formation. Contact of the mold to a thin film ($<$1 μm) results in complete absorption of the resist material and, consequently, no imprint. Furthermore, any nanoscale features formed on the surface of an otherwise thick film of resist will not survive the reactive ion etching process which is needed to transfer these features to the underlying substrate. A recent report has demonstrated that this issue can be ameliorated via fluorinated oxide surface treatment of the PDMS mold.[28]

Herein we report the exploration of a new, simpler, more reliable means of Soft-NIL which overcomes the aforementioned limitations on resist film thickness and does not require modification of the PDMS mold. Easy soft imprint nanolithography (ESINL) enables the use of molds made from inexpensive PDMS in a simple and effective lithographic process to fabricate operating transistor devices. ESINL is enabled by imprinting into a thiol-ene resin that has undergone a partial cure prior to contact with the imprint mold. This simple pre-cure prevents the resist from being absorbed into the PDMS molds and allows for high resolution pattern transfer during the ESINL process. ESINL is the first imprint technique to demonstrate the simplicity and effectiveness of PDMS molds in a true lithographic process capable of fabricating technologically useful nanostructures and as a demonstration has been used to fabricate functional transistor devices.

Experimental Section

Materials. Single sided polished mechanical grade 1.5 in. silicon wafers were purchased from University Wafer while 3 in. highly doped wafers were purchased from Silicon Quest International, Inc. Dow Corning polydimethylsiloxane (PDMS) precursor (Sylgard184) was used. Norland Optical 60 photopolymer resin was acquired from Norland Products. Methanol and 97% chlorodimethyloctylsilane (Fisher), 98% 2-hydroxyethyl methacrylate (HEMA), 98% α,α′-azoisobutyronitrile (AIBN), 98% 1-dodecanethiol, 98% 3-(trimethoxysilyl)propyl methacrylate, 99% hexamethyldisilazane (HMDS), propylene glycol methyl ether acetate (PGMEA) (Sigma-Aldrich), 99.999% gold (Kurt J. Lesker), chromium (R. D. Mathis), 99.995% nickel (Cerac Specialty Inorganics), 99.999% aluminum (Plasmaterials), and Microcircuit Silver type L silver paint (Transene) were used as received. Patterned silicon wafers containing test patterns and transistor structures were fabricated by known photolithographic processes.[32]

Characterization. The UV curing was monitored using a TA Instruments photoDSC (a Q2000 DSC fitted with a UV/vis spot curing accessory). Temperature and energy calibration were performed using an indium standard sample (T_m = 156.6 °C and ΔH = 28.5 J g^{-1}). Aluminum DSC crucibles with 40 mL of capacity were used. All DSC runs were carried out under N$_2$ flow with a flow rate of 20 mL min^{-1}. Film thickness was measured by reflectance with a Filmetrics F20 Thin Film Measurement System. The reported values are an average of at least 10 measurements over the entire surface with a typical standard deviation of ±3 nm. Atomic force microscopy (AFM) images were collected on a Digital Instruments Dimension 3000 Nanoscope in intermittent contact mode under ambient conditions using silicon cantilevers and a scan rate between 0.5 to 1 μm/s. Scanning electron microscope (SEM) images were acquired with a JEOL JSM 6320F field emission gun. Electrical characteristics of the devices were measured with a Signatone H-150 probe station with a Keithley 2602 dual source meter or a Keithley 4200 semiconductor parameter analyzer (Keithley, Cleveland, OH), in ambient air and light.

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Synthesis of Poly(Hydroxymethyl methacrylate) (PHEMA). Ethanol (7.5 mL) was charged in a 25 mL round-bottom flask, and nitrogen was bubbled for 5 min. AIBN (0.07 g, 0.43 mmol), HEMA (5.37 g, 5 mL, and 41.31 mmol), and dodecane thiol (0.43 g, 0.5 mL) were dissolved in the ethanol, the flask was sealed with a rubber stopper, and the solution was heated under N_2 at 60 °C for 4 h with stirring. The solution was cooled and then precipitated dropwise into hexanes. The polymer was filtered, washed with hexanes, and dried to obtain PHEMA (4.5 g, 84%) as a white solid. GPC data (in DMF): $M_n = 32\,353$, PDI = 1.37.

Mold Preparation. Patterned Si masters were cleaned by exposure to O_2 plasma for 3 min, coated with chlorodimethyloctylsilane, and heated to 130 °C for 20 min to create a protective alkyl release layer to ensure proper separation of the cured elastomeric mold. Sylgard 184 base and curing agent components were mixed together in a 10:1 ratio, degassed, cast over the patterned silicon master situated in a polystyrene Petri dish to a mold thickness of about 3.5 mm, and cured for 12 h at 65 °C. After curing, the PDMS was carefully separated from the Si master to yield nanopatterned elastomeric molds.

ESINL UV Imprinting with PDMS Molds. Si substrates were cleaned by rinsing with THF, acetone, and isopropanol and blown dry with a stream of N_2. PHEMA (6.5 wt % in methanol) was applied to the substrate and spun at 3000 rpm for 10 s followed by baking at 130 °C for 30 s forming a 180 nm thick PHEMA film. An adhesion promoter, 3-(trimethoxysilyl)propyl methacrylate, was then applied and spun at 3000 rpm for 5 s and the sample was baked at 130 °C for 1 min. Excess adhesion promoter was washed off by spinning under a pure stream of PGMEA for 15 s at 3000 rpm followed by drying with N_2. Norland Optical 60 (NO60), diluted in PGMEA to specific concentrations and filtered through a 0.45 μm syringe filter, was then applied and spun at 3000 rpm for 15 s. A 40 wt % solution of NO60 was found to work well for imprinting features with a depth of ~700 nm.

Immediately after spin coating, the NO60 film was pre-cured by exposure, in air, to 40 s of 365 nm UV light from a 500 W OAI UV lamp (12.7 mW/cm^2). Immediately thereafter a PDMS mold was placed directly onto the NO60 film and pressed lightly by hand on one corner to initiate propagation of interfacial contact between the two surfaces. Exposure to 365 nm UV light from a 500 W OAI UV lamp under a N_2 blanket for 15 min cured the imprinted photopolymer. Manual demolding, aided by initial separation of the mold and substrate with a razor blade, yielded the final pattern.

Etching, Metal Deposit, Lift-Off. Patterned films were etched in a Trion Technologies Phantom III inductively couple plasma (ICP) reactive ion etcher (RIE) for 7 min under 250 mTorr of O_2 pressure at a flow rate of 49 sccm, with ICP and RIE power of 500 and 25 W, respectively, until the underlying silicon wafer was exposed in the recessed regions throughout the imprint. Etched wafers were coated with approximately 10 nm of various metals by vacuum evaporation. Lift-off was achieved by sonication in warm methanol for 5 to 10 min followed by a methanol rinse.

Fabrication of Organic Field Effect Transistors (OFETs). Highly doped Si wafers (0.001 Ω·cm) with a 100 nm thermal oxide dielectric layer were used as substrates. The wafers were diced into chips approximately 2 cm × 3 cm. Gold interdigitated electrodes shown in Figure 4f were patterned onto the oxide surface by ESINL. Gate electrodes were made by scratching away the oxide layer in an isolated position of the chip with a diamond pen. The freshly revealed underlying Si was coated with a dab of silver paint and baked at 130 °C for 20 min. The completed chip was cleaned with O_2 plasma for 30 s and primed by spin coating hexamethyldisilazane at 3000 rpm for 15 s. Finally, poly(3,3‴-didodecylquaterthiophene) was spun at 1000 rpm for 30 s forming a 45 nm thick film over the entire surface to finish the device. Electrical characteristics of the devices were measured in a Signatone H-150 probe station under a nitrogen atmosphere with a Keithley 2602 dual source meter.

Results and Discussion

Molds were prepared following the well-known procedure for making Sylgard 184 PDMS. Briefly, the PDMS prepolymer base and curing agent solutions were mixed, dispensed over a Si master, and cured. After release from the master the elastomeric molds were ready for imprinting. No special treatment of the PDMS was necessary. Wafers were prepared for imprinting by washing with solvent, drying under N_2, and applying a sacrificial lift-off layer of PHEMA by spin-coating from methanol. PHEMA was chosen as the lift-off material due to its orthogonal solubility to the thiol-ene photopolymer resist but was not critical to the performance of the imprint step itself. An adhesion promoter, 3-(trimethoxysilyl)propyl methacrylate, was applied to the PHEMA surface to provide a surface compatible with the imprint resist. Such preparation can be performed in advance, and the substrates can be stored indefinitely. Coated substrates were washed with PGMEA prior to use to remove any particles present.

Thiol-ene polymers have garnered a great deal of interest due to a number of favorable properties such as initiator-free initiation, controllable cure kinetics, tunable mechanical properties, and lack of polymerization inhibition by oxygen.[33] These reasons, coupled with the wide variety of available thiol and vinyl monomers,[34] have made the examination of these materials attractive for advanced patterning processes, and there have been recent reports concerning their successful use in a number of approaches including replication molding of biostructures,[35] substrates for transfer printing,[36] microfluidic chip fabrication,[37] UV-NIL mold fabrication,[38,39] and high resolution UV-NIL resists.[40]

In this current study, high fidelity imprints were achieved using a typical soft imprint procedure with the addition of a simple but critical step to allow patterning of thin resist films. A thin (~700 nm) film of a commercially available thiol-ene photopolymer resist, Norland Optical 60 (NO60), was applied to the surface of the substrate by spin coating. NO60 is presumed to consist mainly of a urethane-containing tetrafunctional allyl ether (Figure 1) and its thiol counterpart trimethylolpropane tris(2-mercaptoacetate).[41,42] The compo-

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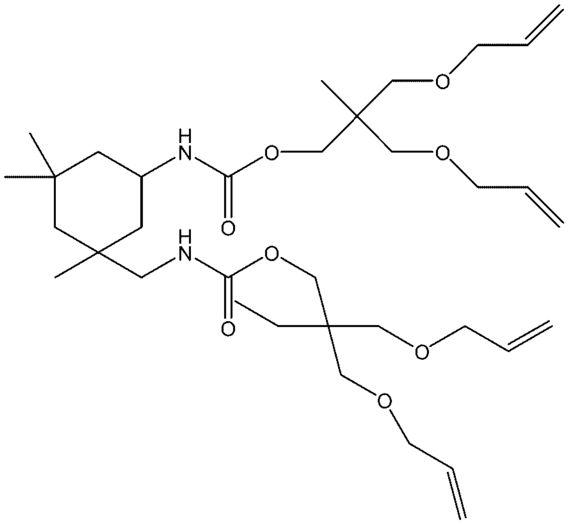

Figure 1. Urethane-based tetrafunctional allyl ene used in thiol-ene polymerizations.

sition may or may not contain a small amount of added photoinitiator as thiol-enes are known to undergo efficient UV photopolymerization in either case.[34] The film was exposed to 365 nm UV radiation using an OAI flood exposure system for about 40 s which caused a partial curing of the resist composition. A PDMS mold was placed onto the film and allowed to form an intimate contact with the coated wafer. The entire assembly was then placed under a N_2 blanket and further exposed to 365 nm UV radiation (12.7 mW/cm^2) to complete curing. The PDMS mold was carefully separated by hand from the substrate, yielding the desired transfer of the pattern into the cured photopolymer layer. High aspect ratio features were preserved during the demolding process due to the low surface energy and bulk modulus of siloxane molds which easily yield during separation. The capacity to directly use PDMS without further processing such as plasma treatment or surface functionalization of the mold not only simplifies the process but also eliminates issues of usability lifetime seen with other forms of soft lithography utilizing modified PDMS.[43–45] As with other Soft-NIL techniques,[11,18–20] once a mold has been fabricated it can be reused numerous times with no deterioration of its imprinting ability. While no effort was made to determine the exact limit of mold integrity we found that over 10 imprints could be done without evidence of pattern deterioration. ESINL presents the additional advantage over other Soft-NIL techniques in that it can be accomplished with organic resist films less than 1 μm thick allowing for subsequent fabrication processes such as deposition and lift-off or reactive ion etching (RIE).

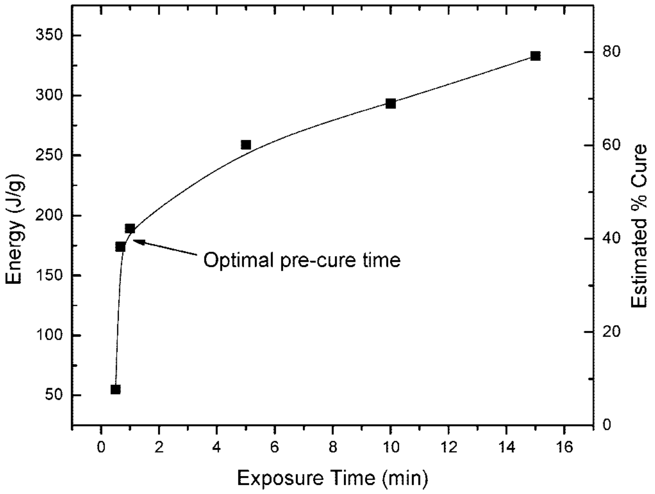

Figure 2. Energy of photopolymerization and estimated extent of cure versus time by photoDSC of NO60 resin was used to determine a quantitative value for the optimal pre-cure point. Optimal pre-cure time corresponds to the point where the polymerization slows, presumably near the gel point. Considering curing is complete in 15 min, it was estimated that an optimal pre-cure time of 40 s corresponds to an extent of cure of 52%.

The effectiveness of this procedure is rooted in the curing mechanism of NO60 resin which cross-links by thiol-ene chemistry.[33] This step-addition type polymerization, in which UV irradiation drives the addition of thiol groups across neighboring double bonds, causes a gradual increase in the MW of the resin until a gel point (α) is reached. At this point the resin diffusion rates are drastically reduced, and mechanical properties increase with vitrification of the polymer. Unlike gelation in acrylate photopolymerizations, which occurs at low conversion and is difficult to predict, the gel point in thiol-enes can be calculated based upon the functionality of the comonomers,[46,47] where α is the extent of reaction at the gel point, f_{thiol} and f_{ene} are the average functionalities of the thiol and ene comonomers, and r is the stoichiometric imbalance.

$$\alpha = [1/r(f_{\text{thiol}} - 1)(f_{\text{ene}} - 1)]^{1/2}$$

As diffusivity and solubility scale inversely with the molecular weight (MW) for diffusants in gels, precuring the spun film for 30−40 s results in MW build-up to a critical MW that is sufficiently high to prevent permeation of the resin into the PDMS stamp while maintaining a low enough viscosity to be rapidly molded by the capillary forces which develop due to the highly conformal contact between the two surfaces.

The curing of NO60 was examined by photoDSC (differential scanning calorimetry under UV exposure). Figure 2 shows the measured exothermic energy of photopolymerization as a function of time. Two distinct regions were observed: a sharp increase in the heat of polymerization (0−30 s) followed by a leveling off of the heat of polymerization. The extent of reaction versus time can be estimated for this reaction by calculating the fraction of energy compared the total energy measured after 15 min of exposure. While this calculation is only an approximation since 100% cure at 15 min cannot be assumed, the observed

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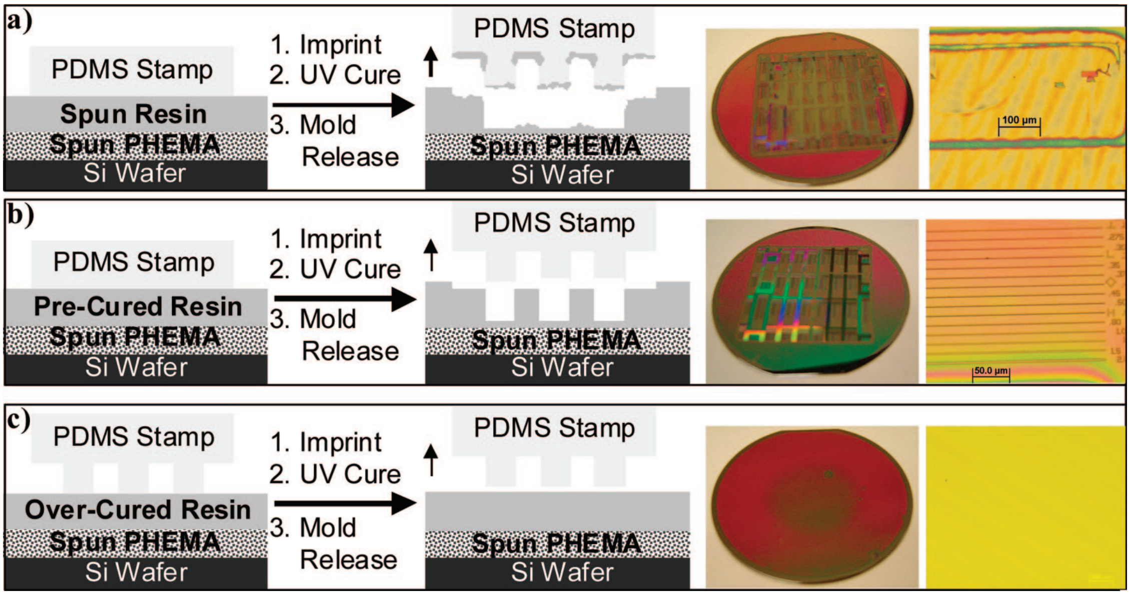

Figure 3. Imprint scenarios and outcomes for Soft-NIL in thin films of NO60. (a) Illustration of a PDMS imprint in a freshly spun film showing absorption of the resist into the mold with corresponding full wafer photograph and micrograph showing exposure of the PHEMA underlayer at points of contact. (b) Illustration of a PDMS imprint in a pre-cured film yielding clean features with corresponding full wafer photograph and micrograph showing imprinted lines ranging in width from 2 μm down to ~300 nm. (c) Illustration of a PDMS imprint in a film which has been pre-cured beyond the point of imprintability with corresponding full wafer photograph and micrograph of the surface showing the absence of features.

change in rate of polymerization at 30−40 s of exposure corresponds to ~40−50% cure, near the theoretical gel point of 41%.

The next step was the experimental determination of the optimal pre-cure time required to promote high resolution imprinting. Attempts were first made to imprint thin films of pristine, non-pre-cured NO60 with PDMS molds (Figure 3a). In these cases, the mold absorbed the resin where contact was made, leaving behind only a smeared underlayer after separation. In contrast, imprinting into a pre-cured resin produced an accurate replica of the mold with resolution of sharp features (Figure 3b). The results of the ESINL process utilizing several different mold sets are shown in optical micrographs in Figure 4a,c,e. AFM of the imprinted surface, depicted in Figure 5, confirms the patterning of well defined 250 nm trenches and lines that matched the profile of the original silicon master. These features represented the lower limit in critical dimensions for our masters; however, it is considered that the scope of resolution for ESINL would be equivalent to typical Soft-NIL capabilities in the range of micrometers down to ~100 nm reliably.[18,20] The window of optimum pre-cure time is rather narrow and was determined by experimentation to be 30−40 s. Shorter exposure times did not prevent absorption of resist by the mold while longer times frustrated complete molding. Eventually, extension of the pre-cure time past a certain point prevented any pattern formation at all (Figure 3c). These observations, supported by the photoDSC data, indicate that optimal imprinting occurs when the resin is at or near the gel point and further curing past the gel point prevents sufficient mobility for the polymer to be effectively molded.

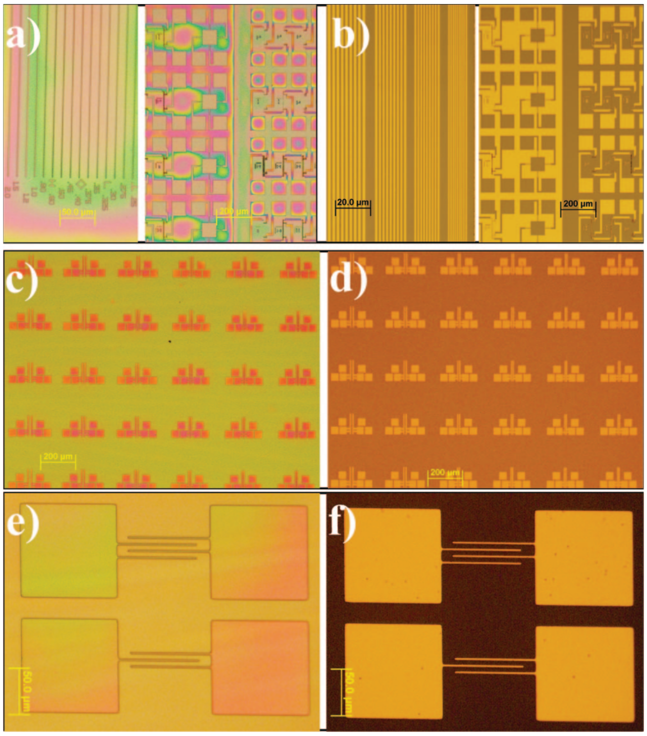

Figure 4. Optical micrographs of (a) imprinted test lines and pads with (b) the corresponding gold structures, (c) imprinted parallel line transistor electrodes with (d) the corresponding gold structures, and (e) imprinted interdigitated transistor electrodes with (f) the corresponding gold structures formed by RIE, vapor deposition, and lift-off.

Imprint resist layers structured by ESINL were very effective in serving as platforms for subsequent patterning of metal structures through traditional lithographic steps. Since the residual resist layer left after ESINL, sometimes referred to as the scum layer, was typically on the order of 100 nm thick, transfer of the patterns to the underlying substrate by plasma etch was easily accomplished. In this step, illustrated in Figure 6, oxygen plasma was used to etch through any remaining NO60 resin in the recessed portions of the imprints as well as the underlying PHEMA lift-off layer. Vacuum evaporation was used to deposit various

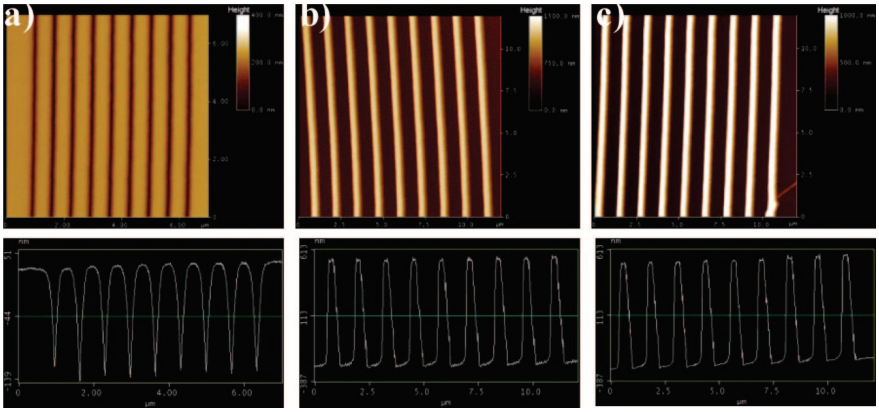

Figure 5. AFM imaging and sectional profile of (a) 250 nm wide and 150 nm deep trenches along with (b) the first replication and (c) the 10th replication of 350 nm wide and 800 nm tall lines imprinted into a 700 nm thick film of NO60.

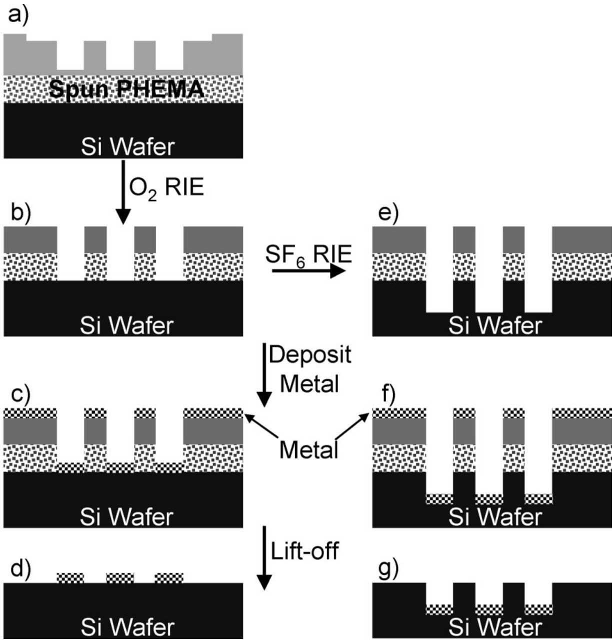

Figure 6. Schematic representation showing the creation of metallic features from patterns formed by ESINL to metallic features. (a) Initial features are formed by imprinting. (b) O_2 RIE is used to break through residual NO60 and the underlying PHEMA lift-off layer. (c) Metal is vapor deposited over the remaining resist and exposed regions of the Si substrate. (d) Lift-off in methanol yields isolated metallic structures on the silicon wafer surface. (e) SF_6 RIE can be employed directly after O_2 etch to transfer features directly into the silicon surface. (f) Metal vapor deposition and (g) lift-off in methanol yield metallic patterns isolated within silicon features.

metals onto the etched patterns, and lift-off in methanol yielded the final metallic pattern on the Si substrate surface. Fully patterned 2 inch wafers are shown in Figure 7 where features are replicated in gold, nickel, and aluminum. In Figure 7d, after the inital oxygen breakthrough etch, an SF_6 etch was used to transfer patterns directly into the underlying silicon substrate followed by metal evaporation to produce aluminum coated silicon features.

To demonstrate the ease and effectiveness of ESINL for producing arrays of device structures the technique was used for applications in organic transistors. Device structures for organic field effect transistors (OFETs) were prepared by dicing a highly doped Si wafer coated with a thermally grown oxide layer. Arrays of source and drain electrodes as those

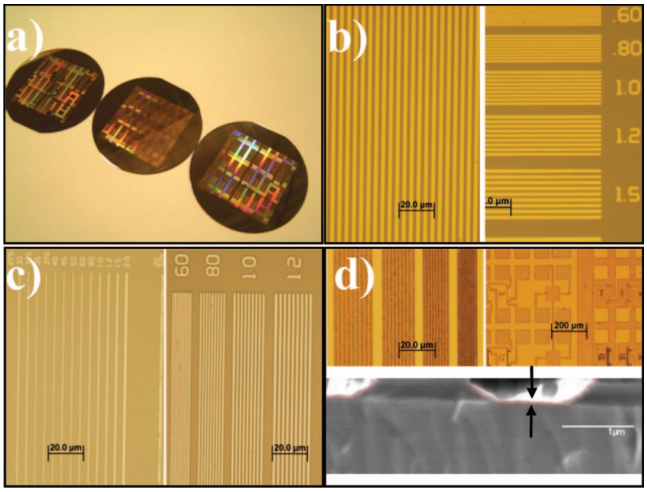

Figure 7. Images of patterned metallic structures on Si wafers fabricated by the ESINL technique. (a) Three 1.5 in. diameter fully patterned wafers showing transfer to gold, nickel, and aluminum capped silicon features. Corresponding micrographs are presented of (b) gold lines, (c) nickel lines, and (d) aluminum coated Si lines and pads with cross-sectional SEM showing an Al (outlined in light red) covered trench between Si features. Black scale bars indicate 20 μm.

shown in Figure 4e,f were patterned on each device following the ESINL procedure using gold as the deposited metal. A commercially available (American Dye Source) organic semiconductor, poly(3,3‴-didodecylquaterthiophene) (PQT12), was spun cast onto a device to form the semiconducting organic layer of about 45 nm. Figure 8 shows the output and transfer characteristics of a bottom-contact PQT12 transistor characterized under an inert atmosphere. The output curves (Figure 8a) show well-resolved curves with excellent current modulation as the gate voltage is gradually increased from 0 V to −30V. Figure 8b shows the transfer characteristics of the same device with a current on/off ratio of 6.0×10^4, threshold voltage of 2.0 V, and a field-effect mobility of 6.0×10^{-3} cm^2/(V·s) for a device with a channel width (W) of 1020 μm and a channel length (L) of 5 μm. The mobility of these transistors are somewhat lower than optimized conditions from literature reports;[48] however, such results are expected from as-received, unpurified polymer samples. These results also represent one of the first

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(48) Panzer, M. J.; Frisbie, C. D. *J. Am. Chem. Soc.* **2007**, *129*, 6599–6607.

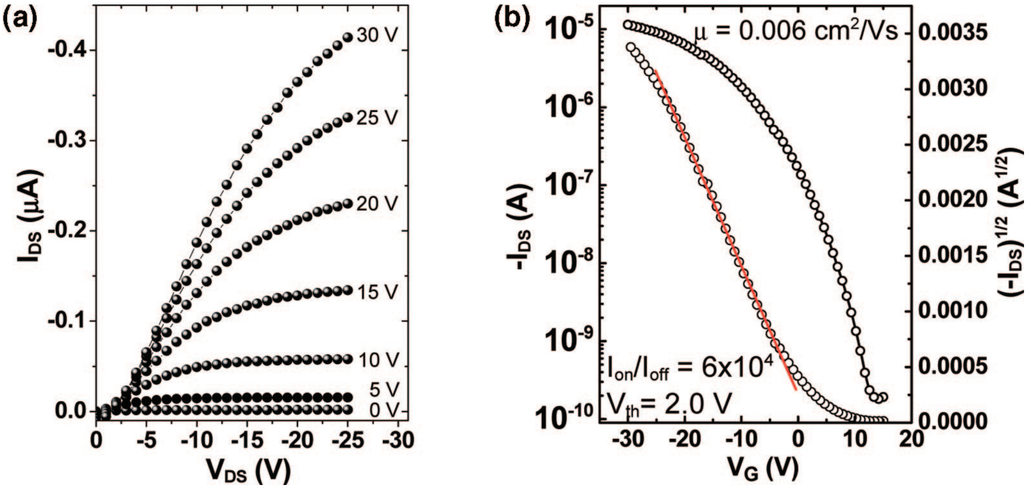

Figure 8. Electrical characteristics of a PQT12 OFET with $W/L = 204$. (a) P-channel output characteristics and (b) transfer/square-root characteristics for the same device at a constant source-drain voltage of −25 V.

characterizations of an organic semiconductor device fabricated via *soft imprinting* with PDMS. In this manner ESINL has been shown to provide a simple yet effective technique for fabricating device structures normally achievable with more sophisticated and costly photolithographic or NIL tools. Our technique has great prospect in applications where highly sophisticated device structures are required such as those in complementary logic, sensors, and new device technologies.

Conclusion

ESINL using a PDMS mold has been shown to effectively pattern thin films of a partially cured thiol-ene photopolymer. The extent of the pre-cure to achieve an optimal MW dictates the resin performance, and imprinting under such conditions is an effective means for replicating nanoscale features over large areas (~6 cm^2) in a single patterning step. The PDMS mold surface required no special treatments, hence the same mold can be used a number of times with no need for reworking between imprints. In ESINL there is no heating, minimal applied pressure, no substrate surface chemistry, and many imprints achievable from a single mold. The power of this technique stems from combining the superior patterning abilities of soft-lithography with the lithographic capabilities of hard quartz, metal, or silicon mold based imprinting in thin films. Fabrication of metallic structures from the imprinted resist is straightforward using well established pattern transfer methods such as anisotropic plasma etch, vapor deposition, and lift-off. Furthermore, ESINL provides an accessible means for fabricating nanoscale device structures of various material architectures without the need for advanced lithography tools. As a demonstration of the application of our technique, we fabricated organic field-effect transistors that exhibited excellent characteristics. We are currently designing integrated circuit platforms and various other sophisticated architectures for use in electronic devices.

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