Fuming Method for Micropatterning Structures on Langmuir-Blodgett Films

Elizabeth S. Erickson, **Philip W. Livanec**, **Jessica F. Frisz**, and **Robert C. Dunn**
Ralph N. Adams Institute for Bioanalytical Chemistry, Department of Chemistry, University of Kansas, Multidisciplinary Research Building, 2030 Becker Dr., Lawrence, Kansas 66047

Robert C. Dunn: rdunn@ku.edu

Abstract

Lipid monolayers of L-α-dipalmitoylphosphatidylcholine (DPPC) are used to pattern substrates using the Langmuir-Blodgett (LB) technique. Lipid monolayers are deposited onto a freshly cleaved mica surface or glass capillary under conditions that lead to distinct patterns in the film. Exposure of the supported monolayer to ethyl 2-cyanoacrylate fumes leads to preferential polymerization in the more hydrated regions of the patterned monolayer. This method enables surfaces to be micropatterned where the lateral features are controlled by the structure present in the underlying LB film and the vertical feature size is controlled by the length of the fuming process. Atomic force microscopy (AFM) measurements confirm that the original structure in the LB film is preserved following fuming and that the lateral and vertical feature sizes can be controlled from nanometers to microns. This method, therefore, provides a rapid and versatile approach for micropatterning both flat and curved surfaces on a variety of substrates.

Introduction

Exploring and developing new methods for fabricating and manipulating structures on the submicron length scale have rapidly developed over the last decade. Interest in these structures revolves around potential applications in fields such as sensing, drug delivery, or analysis on miniaturized platforms.[1–3] These applications often take advantage of miniaturization to increase performance characteristics of a particular device or exploit unique phenomena that arise as a result of the reduced dimension. As a result, much activity has centered on developing new methods for rapidly patterning surfaces.[4]

Patterning techniques are often classified as conventional or unconventional depending on their stage of development.[5–7] Conventional techniques are considered the more developed methods that are commercially available and utilized in manufacturing. This category includes methods such as photolithography and particle beam lithography, which are widely adopted in industry and form the mainstay of many manufacturing processes in the microelectronics industry.[7, 8] Photolithography approaches are rapid and allow for patterning large surface areas in parallel while serial techniques, such as particle beam lithography, are slower but generally enable higher spatial resolution. Together these techniques provide powerful capabilities for micropatterning surfaces. However, they often require expensive equipment, have limited flexibility in the materials patterned, and generally do not work well on curved substrates. These and other limitations have led to research exploring unconventional micropatterning approaches.

Correspondence to: Robert C. Dunn, rdunn@ku.edu.

A great deal of research has explored methods classified as soft lithographic approaches which have proven versatile for patterning structures onto surfaces.[5, 9] In general, these approaches use a master manufactured using a conventional approach to act as a form for creating a polymer mold or stamp.[5] These methods enable many replicas to be manufactured from a single master, thus relaxing the reliance on expensive instrumentation. These techniques can pattern large surface areas with sub-100 nm features and are amenable to patterning curved surfaces.[10] For even smaller features, scanning probe microscopy has proven useful.

Scanning probe techniques such as scanning tunneling microscopy (STM) and atomic force microscopy (AFM) have been adapted for patterning surfaces down to the atomic level.[11] Techniques such as dip-pen nanolithography use the transfer of material from an AFM tip to the substrate to write features as small as ~10 nm onto a substrate.[12, 13] While these techniques offer exquisite control over the lateral feature size, the serial nature of the process makes them generally slow. This, however, is beginning to be addressed with the development of multi-tip platforms that enable the parallel writing of features.

Other approaches for micropatterning surfaces have taken advantage of natural structures formed in thin films. Inorganic films, di-block copolymers, and self-assembled monolayers can all be used to produce highly ordered, repeating structures on surfaces.[14–16] The Langmuir-Blodgett (LB) technique has been extensively used to study the two-dimensional phase structure present in lipid monolayers and multi-layer films transferred onto a solid support.[17–23] The phase structure present in the resulting LB monolayer leads to long range patterns in the film, the particular structure of which is influenced by the components of the film and the conditions used to transfer the film onto the support. These two-dimensional films, however, have found limited applications in microfabrication due to challenges associated with extending these structures into the third dimension. Therefore, while the LB approach allows for periodic structures to be patterned onto surfaces rapidly, modifying and controlling the feature height has proven problematic.

Here we demonstrate a technique for micropatterning surfaces that is rapid and offers a high degree of control over both the lateral and vertical feature size. This method uses the LB technique to transfer a lipid monolayer onto a substrate under conditions that leads to the formation of distinct two-dimensional structures. We take advantage of the patterns formed in the LB film to template the growth of a polymer using a fuming method. In the fuming method, a supported lipid LB film is exposed to fumes from a cyanoacrylate, such as ethyl 2-cyanoacrylate.[24] The cyanoacrylate molecules undergo anionic polymerization in the presence of a weak Lewis base, such as water, to form a strong durable polymer. The different hydration levels of the structures formed in the underlying LB film, therefore, template the growth of the polymer. This process leads to the growth of three-dimensional structures with lateral dimension controlled by the structure present in the underlying LB film and vertical dimension controlled by the length of the fuming process. Using this technique, we show that structures can be fabricated onto both flat and curved surfaces with nanometric control.

Experimental Section

Langmuir-Blodgett Deposition

L-α-dipalmitoylphosphatidylcholine (DPPC) (Avanti Polar Lipids, Alabaster, AL) was dissolved in spectral grade chloroform (Fisher Scientific, Fairlawn, NJ) at a concentration of 1 mg/mL. Approximately 50 μL of the DPPC solution was dispersed onto a water subphase (18 MΩ) in a computer controlled Langmuir-Blodgett (LB) trough (Model 611, Nima Technology, Coventry, England). The suspended lipid monolayer was compressed at a rate

of 100 cm^2/min to the desired surface pressure, which was monitored with a Wilhelmy pressure sensor. DPPC monolayers were transferred onto a freshly cleaved mica substrate in a head group down arrangement (Y-type). For experiments on curved substrates, DPPC monolayers were transferred onto 1.0 mm O.D. × 0.75 mm I.D. borosilicate glass capillaries (Sutter Instrument, Novato, CA). Films were transferred at a rates ranging from 10 – 40 mm/min, depending on the patterning desired. All films were transferred from a subphase held at ~ 21 °C.

Cyanoacrylate Fuming

Following LB deposition of DPPC onto a substrate, films were exposed to fumes from the cyanoacrylic resin, ethyl 2-cyanoacylate (Sigma-Aldrich, St. Louis, MO). Briefly, the supported DPPC monolayer was transferred into a sealed chamber containing approximately 0.03 g of ethyl 2-cyanoacrylate. Prior to sample introduction, the cyanoacrylate resin was heated to ~ 50 °C using a heat lamp to accelerate the fuming process. Following cyanoacrylate heating, the LB film was introduced into the sealed chamber and exposed to the cyanoacrylate fumes for seconds to minutes, depending on the vertical feature size desired.

Atomic Force Microscopy

Atomic force microscopy (AFM) measurements (Nanoscope IIIa, Veeco Instruments, Santa Barbara, CA) were carried out in contact mode using silicon nitride cantilevers with a spring constant of 0.12 N/m (Veeco Instruments, Santa Barbara, CA).

Results and Discussion

The pressure isotherm for DPPC, such as that shown in Fig. 1, has been thoroughly studied and exhibits a plateau region at low surface pressures where the liquid-expanded (LE) and liquid-condensed (LC) phases coexist.[21] LB films of DPPC can exhibit distinct patterns that are sensitive to the surface pressure and conditions under which the film is transferred onto the substrate.[20] For example, LB monolayers of DPPC transferred in the phase coexistence region of the pressure isotherm exhibit distinctive semi-circular LC domains surrounded by LE regions in the monolayer. At lower surface pressures and faster dipping velocities, previous studies have found that hydrodynamic instabilities lead to the formation of stripes in the films.[18]

Figure 2A shows an AFM image of a typical DPPC monolayer transferred under conditions that lead to the formation of stripes. The DPPC monolayer was deposited onto a mica substrate at a surface pressure of 3.0 mN/m and a dipping velocity of 10 mm/min. Previous studies have shown that at these elevated dipping velocities, wetting instabilities lead to films with hydrophilic stripes separated by lipid regions that are hydrophobic. The stripes are observed as small height differences in the 20 μm × 20 μm AFM image shown in Fig. 2A. There is a small ~ 1 nm height difference between the hydrophilic stripes and the taller hydrophobic lipid regions as shown in the line-cut in Fig. 2A. Under these particular transfer conditions, the widths of the hydrophilic and hydrophobic stripes are ~0.85 μm and ~3.0 μm, respectively.

Figure 2B shows a similar DPPC film that was subsequently exposed to fumes of ethyl 2-cyanoacrylate for approximately 2 minutes following transfer onto the mica substrate. The stripes in the film are still clearly visible, however, as the line-cut displayed in Fig. 2B shows, the height differential has now grown to ~ 150 nm. By exposing the LB film to the cyanoacrylate fumes, a preferential polymerization reaction takes place in the hydrophilic regions of the film which can be used to build up three dimensional structures. The origin of

this is understood from the reaction mechanism shown in Scheme 1 and the schematic shown in Fig. 3.

Cyanoacrylate molecules undergo anionic polymerization in the presence of a weak Lewis base, such as water, to form a strong durable polymer. The patterned hydrophilic and hydrophobic areas in the LB film, therefore, provide a template that dictates where the polymerization reaction can proceed as shown in Fig. 3. For the films shown in Fig. 2, therefore, the narrow hydrophilic stripes preferentially support the polymerization reaction leading to the increase in their height.

It is also straightforward to modify the size and spacing of the channels through changes in the film transfer conditions and fuming length. As an example, Fig. 4 shows a range of channels fabricated by varying these conditions. Figures 4A, 4B, and 4C display channels that are 530 nm, 700 nm, and 3.0 μm wide, respectively, templated by increasing the velocity at which the LB film was transferred. The average height profiles displayed, moreover, show that the channel depths are 15 nm, 100 nm, and 150 nm, respectively, reflecting changes in exposure times during the fuming process. With this approach, vertical features from a few nanometers to microns can be fabricated in minutes.

Another advantage of this approach is that large surfaces can quickly be micropatterned since the entire surface is exposed during the fuming process. As an example, Fig. 5 shows a 60 μm × 60 μm region of a film that was templated with a DPPC monolayer transferred to mica at a surface pressure of 3.0 mN/m and a dipping velocity of 10 mm/min. Exposure to cyanoacrylate fumes for ~ 1 minute leads to the formation of enclosed channels, approximately 100 nm deep. The line-cut shown below the image in Fig. 5 reveals the long range order present in these microfabricated structures.

The fuming process can also be used to grow three dimensional structures directly onto the lipid monolayer. Monolayers of DPPC transferred in the LE/LC phase coexistence region of the pressure isotherm lead to distinct patterns in the resulting films. Generally, these films consist of semi-circular LC lipid domains surrounded by the more expanded LE phase. While these monolayers lead to generally hydrophobic surfaces due to the exposed lipid tail groups, greater access to the polar headgroups and underlying hydrophilic mica substrate in the disordered LE phase leads to preferential hydration compared to the more ordered and closely packed LC phase.

Transferring DPPC monolayers to a mica substrate at slower speeds and higher surface pressures enables wells to be patterned onto the substrate, as shown by the films displayed in Fig. 6. For the films shown in Fig. 6, DPPC monolayers were transferred onto mica at a surface pressure of 8.5 mN/m and dipping velocity of 10 mm/min. Under these conditions, the films contain semi-circular LC domains that are 5–8 Å taller than the surrounding LE phase, consistent with previous measurements on similar films. Figure 6A shows a film transferred under these conditions, following fuming with cyanoacrylate for 2 minutes. The line-cut shown indicates that the vertical structures in this film are 140 nm. The fuming process leads to polymer growth in the LE regions of the film, creating wells in the film where the semi-circular LC domains are located. The film shown in Fig. 6B was fumed for 10 minutes and the well depth is ~ 450 nm.

The series of films shown in Figs. 4 and 6 help to illustrate that the fuming method provides a fast, flexible approach for micropatterning surfaces with nanometer to micron control over both the lateral and vertical feature size. While the LB film on the substrate templates the lateral features, the vertical feature size is controlled through the fuming step. Using LB films to template the lateral pattern offers several advantages: different surface active molecules lead to other geometrical patterns, film transfer is rapid even for large surface

areas, a range of substrates can be used, and films can be transferred to both flat and curved surfaces. To illustrate the latter, fuming experiments were conducted on LB films transferred onto the outer walls of small glass capillaries.

Figure 7 shows the results from fuming a DPPC monolayer transferred onto the outer surface of a glass capillary (outer diameter = 1.0 mm) at a surface pressure of 8.5 mN/m and dipping velocity of 10 mm/min. As shown in Fig. 7, a fluorescence image of the capillary surface reveals coexisting bright and dark structures in the film that are indicative of DPPC phase coexistence. This confirms that an intact monolayer is transferred onto the outside of the glass capillary using the LB method. Also shown in Fig. 7 is an AFM image of the capillary surface following fuming. The AFM image shows that the lateral structure present in the film is preserved following fuming while the height difference is increased to ~ 30 nm. In contrast to films transferred onto hydrophilic mica surfaces where polymerization occurs in the LE regions of the film, those transferred onto glass exhibit preferential polymerization in the LC regions of the monolayer. This reflects the more hydrophobic nature of the underlying glass substrate and shows that both the LB film and substrate are important in directing polymer growth. The results presented in Fig. 7 show that the fuming method can be used to micropattern highly curved surfaces, which have proven problematic for other approaches.

These results show that LB films transferred onto both flat and curved substrates can be used to template lateral features for micropatterning using the fuming method. The vertical feature size is controlled through the fuming step, which offers advantages that compliment current micropatterning techniques. In the fuming method, vertical features can be easily tuned from nanometers to microns by controlling the exposure time to the cyanoacrylate fumes, providing a large dynamic range of feature sizes. Since it is a parallel approach, fuming takes minutes regardless of substrate size and cyanoacrylates have easily accessible functional groups for chemically modifying the surface properties of the patterned substrate. Cyanoacrylates are also amenable to autoclaving for biological applications and are transparent which should facilitate the development of applications involving optical approaches.[25]

Conclusions

A method for micropatterning flat and curved surfaces is developed that uses LB films to template the growth of a polymer on a substrate. Patterns in LB films arising either from hydrodynamic instabilities during the dipping step or phase partitioning in the lipid monolayer are used to template different hydration levels across the film. Upon exposure to fumes from ethyl 2-cyanoacrylate, anionic polymerization occurs in the hydrated regions of the film leading to polymer growth in those areas. Feature height is controlled by the duration of the fuming step and structures from nanometers to microns can be fabricated in minutes. This method offers a general approach for patterning surfaces that is rapid, amenable to different substrates and films, will work on both flat and curved surfaces, and does not require expensive instrumentation.

Acknowledgments

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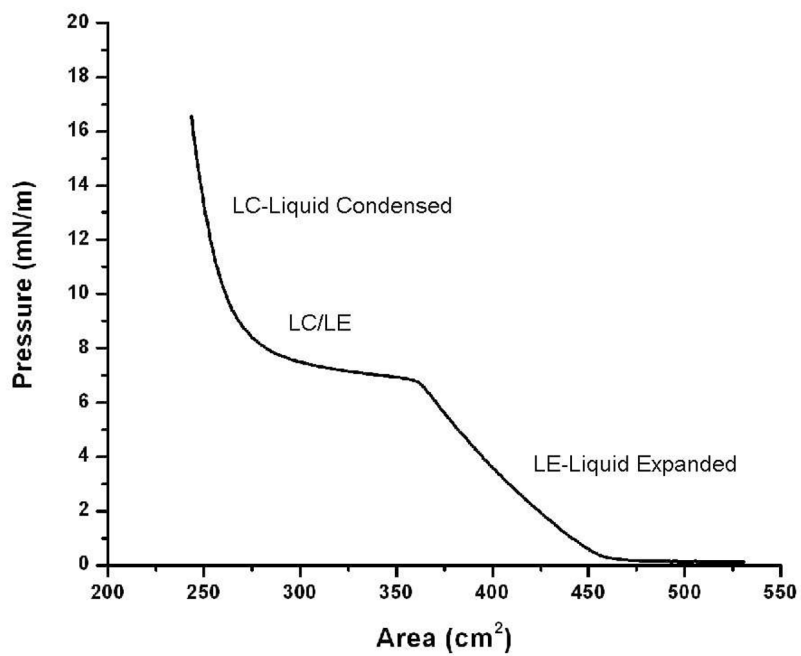
Figure 1.
Pressure isotherm for the compression of a DPPC monolayer dispersed on a water subphase held at ~ 21 °C.
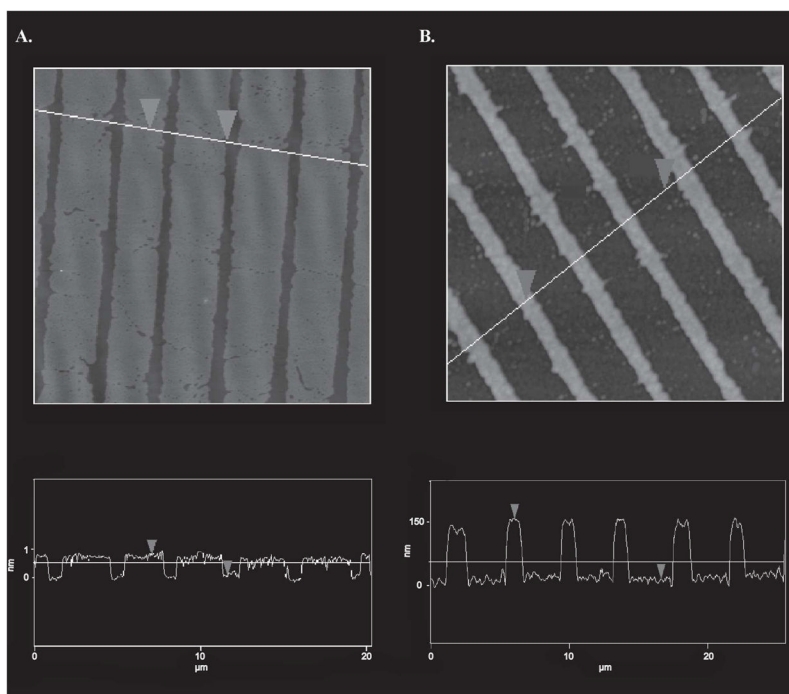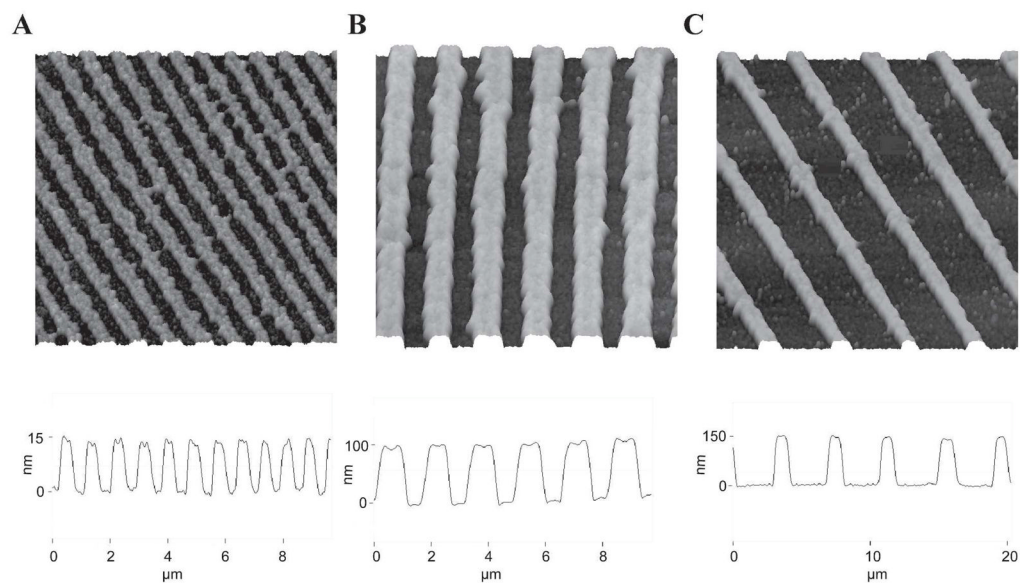
Figure 2.
(**A**) AFM image of a LB film of DPPC transferred onto mica under conditions that lead to the formation of stripes in the film. The line-cut shown below reveals a ~ 1 nm height difference between the hydrophobic lipid stripes and the mica substrate. (**B**) A similar film following fuming with ethyl 2-cyanoacylate for approximately 2 minutes. Preferential polymerization in the hydrophilic regions of the film leads to the formation of channels. The line-cut below shows that the difference in feature height is now ~ 150 nm following polymer growth.
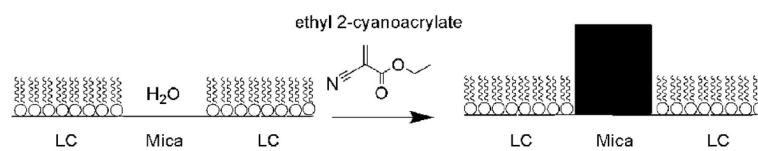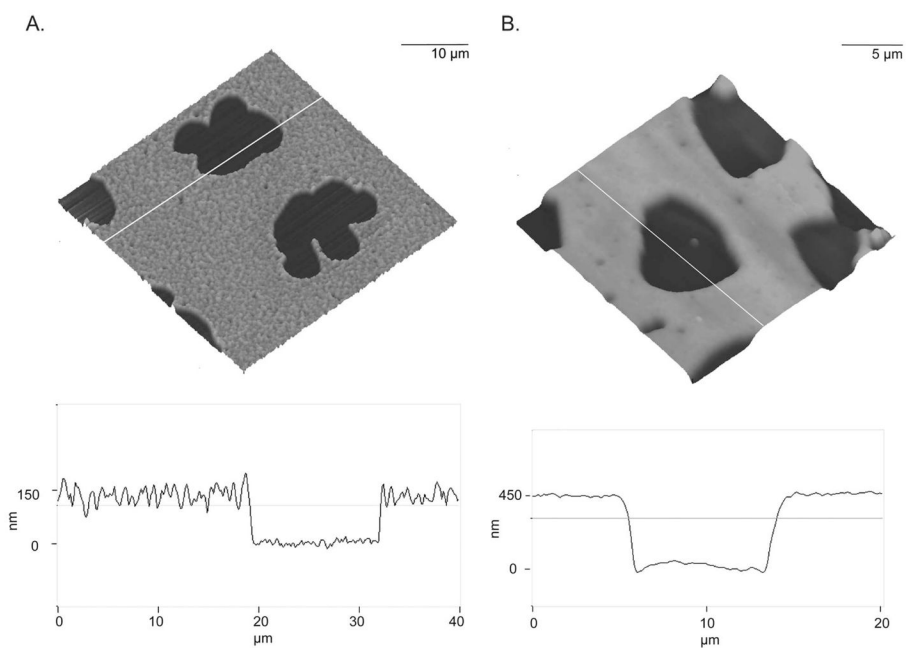
Figure 3.
Schematic representation of the polymerization process. Hydrophilic regions in the deposited LB film lead to the preferential polymerization and growth of three dimensional structures.
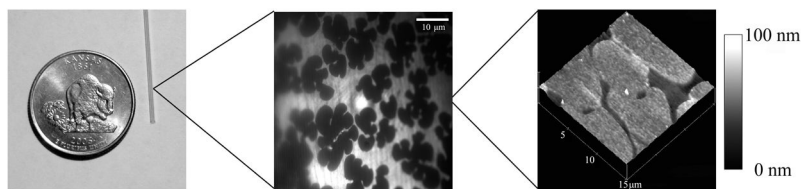
Figure 4.
Series of AFM images illustrating the flexibility in channel dimensions created with the fuming method. The channels shown are (**A**) 530 nm wide and 15 nm deep (Π = 3 mN/m, dipping velocity = 40 mm/min, fumed for 2 minutes); (**B**) 700 nm wide and 100 nm deep (Π = 3 mN/m, dipping velocity = 25 mm/min, fumed for ~ 1 minute); and (**C**) 3.0 µm wide and 150 nm deep (Π = 3 mN/m, dipping velocity = 10 mm/min, fumed for ~ 30 seconds). The channel width is controlled by the underlying LB film and the depth is controlled by fuming duration.
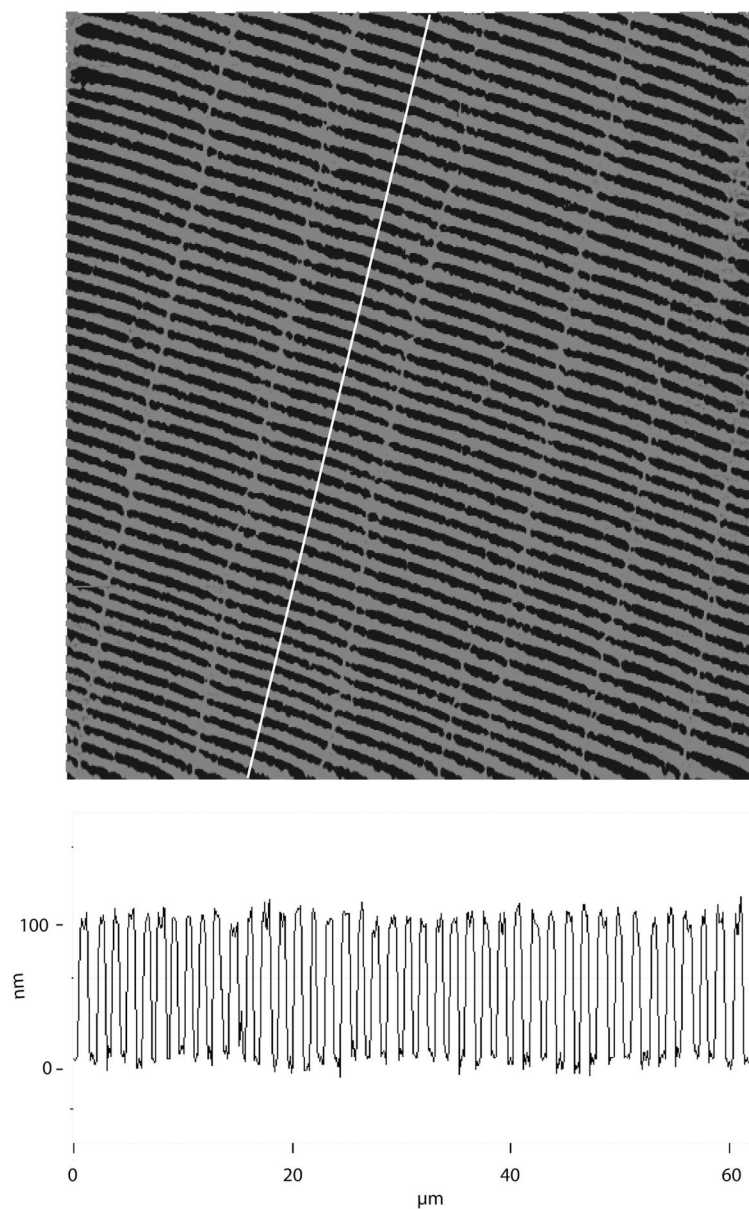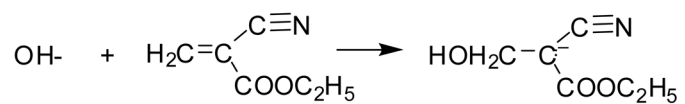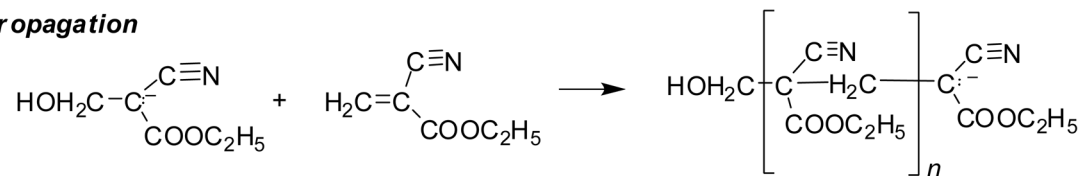
Figure 5.
A 60 µm × 60 µm AFM image of a fumed film with enclosed channels approximately 100 nm deep. The line-cut shown below illustrates the long range consistency in the features grown on the underlying LB film.

Figure 6.
AFM images of DPPC monolayers transferred in the LE/LC phase coexistence region following fuming. Fuming leads to preferential polymerization in the LE regions of the film, leading to the formation of wells in the semi-circular LC domains. The wells in the films are (**A**) ~ 140 nm and (**B**) ~ 450 nm deep.

Figure 7.
(**Left panel**) A Glass capillary tube (1.0 mm O.D. 0.75 mm I.D.) shown next to a U.S. quarter (23 mm diameter) for scale. (**Center panel**) Fluorescence image of a DPPC monolayer transferred onto the outer surface of a capillary tube using the LB technique. The bright and dark structures observed in the fluorescence image are typical of DPPC monolayers transferred in the LE/LC phase coexistence region of the pressure isotherm (~8.5 mN/m). (**Right panel**) A 15 µm × 15 µm AFM image of the outer surface of the DPPC coated capillary following fuming. Following fuming, the height differences in the DPPC film increase to ~ 30 nm while the lateral structure remains the same.

Initation

Propagation

Scheme 1.