Electro-hydrodynamic instability patterning of polymers

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Abstract. Electro-HydroDynamic Instability Patterning, EHDIP, is a novel micro-manufacturing process that makes use of the instability of viscous polymeric thin films when exposed to electrostatic fields. By using non uniform electrostatic fields, it is possible to shape the polymer into defined meso- and micro-scale structures which are subsequently cured to defined 2D and 3D microstructures. The relatively rapid process time, the one-step manufacturing approach, as well as the ability to produce hitherto unrealised topographies - such as continuous profile structures, makes EHDIP an attractive manufacturing process.

1. Introduction

The last decade has witnessed an expanding literature examining the effects of electrostatic fields upon the fluid-fluid interface of polarisable leaky dielectrics [1][2]. These studies have demonstrated the formation of structures under uniform and non uniform E-fields. The phenomenon, called here electro-hydrodynamic instability patterning or EHDIP, offers several advantages over traditional photolithographic methods. Firstly, as it is a maskless method, no expensive optical equipment or photomask are needed. Secondly, a large range of polymer materials are, in principle, suitable for this technique, allowing thereby the possibility to use cheaper resists for the patterning of thick structures. Thirdly, there is no further polymer development process needed due to the one-step pattern formation after annealing of the polymer material. This article describes the progress made towards the modeling and experimental characterization of this process.

2. Theory and modeling

The combination of the Navier-Stokes equation [1],

\[ \rho (\partial_t v + (v \cdot \nabla)v) = -\nabla p + \eta \Delta v + f \] (1)

And the body force term, \( f \), coupled to the electromagnetic forces through the Maxwell stress tensor as derived by Landau [1],

\[ f = QE - \frac{1}{2}E^2 \nabla \varepsilon + \frac{1}{2} \left[ \rho \frac{dz}{d\rho} \right]_0 E^2 \] (2)
Constitute the basis of the modelling of the EHDIP process. In the first equation, the fluid stress is the sum of a diffusing viscous term, proportional to the gradient of the fluid velocity, \( \nu \), and a pressure term. In the second equation, the first term on the R.H.S. is the Coulomb force, the second term is the dielectric force and the last term is the electrostrictive force.

The pressure of the electrostatic force at the interface between air and the polymer causes a deformation in the polymer surface. This deformation is more pronounced and quicker in areas where the field is stronger. A patterned metal mask subjected to an electric potential will create a strong non-uniform field that will redistribute the volume of the polymer into lateral mesas with the same dimensions as the mask, effectively transferring the mask pattern to the target polymer [3].

2.1 Schwarz-Christoffel mapping and COMSOL™ simulation

The complex electrostatic field distribution at the interface was computationally modeled using the multiphysics modelling software package COMSOL™. Simulation results are provided in fig.1 and shows strong non-uniformity of the electrostatic field near the surface of metal mask. In the simulation, the mask is taken a binary grating; the redistribution of volume of the polymer is schematically described by fig.2.

An analytical solution of the electrostatic field would be desirable such that it can into the previous two equations. In that end, the Schwarz-Christoffel (SC) conformal mapping has been used to map the binary structure onto a specific complex plane in order to solve the electrostatic potential problem more easily [5]. This method allows for the binary structure described above to be mapped from the spatial domain \((z)\) to an auxiliary plane \((w)\). The complex co-ordinates \((x, y)\) in the \(z\)-domain are mapped to the axes \((u, v)\) of the \(w\)-domain. The basic SC equation is as follows:

\[
z(w) = \prod (w - a_j)^{\alpha_j} + k \tag{3}\]

Where \(a_j\) are the pre-vertices and \(\alpha_j\) is the turning angle of the boundary in the \(z\)-domain. The two constant parameters, \(C\) and \(K\), affect the scaling and the positioning of the conformal map, respectively. By selecting the correct pre-vertices it is possible to construct a conformal map of a periodic binary pattern like that seen in the experimental set up. For every period, one vertex is set to infinity creating thereby a map of periodic trigons, where the two top vertices have 90° turning angles. This allows us to construct the map function:

\[
z(w) = \frac{l}{\pi} \int \frac{\cos \left( \frac{\pi w}{l} \right) + \cos \left( \frac{\pi}{l} \right)}{\cos \left( \frac{\pi w}{l} \right) + 1} \, dw \tag{4}\]
The electric field strength and electrostatic pressure at the fluid interface can be computed and compared to the COMSOL™ simulation results as shown in (fig.3) where the continuous lines show the COMSOL modeling and the points show the SC mapping, it was observed that there is a very close correlation in the two methods at the points of interest, where the field is highest underneath the mask protrusions:

![Figure 3: SC vs. COMSOL™ electrostatic field modelling results](image)

**3. Experimental set up and real time sensing**

In order to properly characterise the EHDIP process, a mechanical rig was built to allow for six degrees of freedom of movement. Linear Variable Differential Transformers (LVDT) and a three-axis accelerometer were configured for static angle readings to control the orientation of the rigs stages and the separation of the mask from the polymer surface. A vacuum chuck was used to suspend the mask above the surface as shown in fig.2. The rig accommodates a hot plate upon which rests a wafer with the spun-on polymer. The temperature is raised beyond the glass transition temperature of the polymer, to allow the redistribution of the polymer volume. The electric field is then applied to the mask through the conductive vacuum chuck.

In order to examine the real time effects of the polymer growth in the micron sized gap between the mask and target polymer, we manufactured a capacitive sensing system that measures the change in polymer volume as a function of time. This allowed us to measure the instantaneous change in the target material as shown in fig.5.

![Figure 4: Time evolution of the polymer volume](image)

![Figure 5: Example of LCP mask](image)

We were able to characterise the change of polymer volume over time and observe the effect of different magnitudes of electrostatic fields on the interface. We observed that the majority of polymer displacement occurred early in the process time.
4. Mask design
EHDIP is wholly dependent upon the use of the non uniform electrostatic fields generated by the binary gratings, used here as the master electrode. The electrode was manufactured using the LIGA process [6]. This method involved the photolithographic development of a pattern into a polymer photoresist spun on a wafer with a suitable seed layer for the subsequent electroforming process. An alternative, and somewhat simpler process, was also implemented using copper clad Liquid Crystal Polymer (LCP) as shown in fig.6. LCP is a dielectric material chosen for its large breakdown potential, and its ability to be fabricated in very thin thicknesses. LCP is usually clad on both sides by a copper sheet. One side of the copper is patterned using well proven PCB development techniques, leaving exposed LCP patterns in the underside copper. A large electric potential is applied to the undeveloped copper side, and a much lower electric potential is applied to the developed side. This gives rise to a field effect where depletion regions build up in the areas adjacent to the developed copper areas. The electric field developed by the large potential is effectively shaped by these regions and concentrates in the exposed LCP areas. By choosing appropriate patterns for development, it is possible to shape the E-field in the same dimensions as that achieved using traditional LIGA techniques in a much shorter time frame and with less demanding mechanical properties.

5. Experimental results and discussion
A full factorial experiment was carried out in order to identify the most important factors promoting the polymer growth. Our investigation looked at the applied potential, the temperature applied to the polymer, the film thickness of the target polymer, and the separation (air gap) between the mask and the polymer. The properties examined were the average growth rates at the corner and middle of the structures as well as the uniformity of the structure dimensions over the patterned area.

The most important factor influencing both growth and uniformity is the film thickness. A greater thickness causes greater undulations in the target material fluid interface. A thicker film allows for more available material for redistribution than thinner films, thereby increasing uniformity. We observed that greater temperatures caused the solvent in thinner films to dissolve quicker, retarding growth rates, while larger air gaps induced a larger thermal flow, the effect of which is to increase the surface pressure on some parts of the film but not others, negatively influencing uniformity. EHDIP is usable with a broad class of materials; any polarisable polymer fluid can be used in the process. EHDIP also has several advantages with respect to traditional polymer machining techniques. It is a non contact process, making it suitable for constructing devices for bio-MEMS fields where contamination is a risk; the non contact also prolongs the useful life of the mask as well. It is a one step process, capable of completing a useful microstructure in two minutes, after curing. We also observed the formation of continuous curved surfaces, opening the possibility of creating new micro devices for optical and microfluidic applications, such as hydro dynamically efficient micro channels, diffraction gratings and lenses for short wavelengths.

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