Chapter 8

CONCLUSIONS AND SUGGESTED EXPERIMENTAL IMPROVEMENTS

My thesis has been broadly presented in two parts. The first part contained Ch. 2, Ch. 3, Ch. 4, and Ch. 5 and dealt primarily with basic scientific investigations of nanofilm instabilities. Specifically, we investigated the dominant physical mechanism behind a thin film instability driven by large transverse thermal gradients. We determined that the dominant mechanism was thermocapillary forces which act along the nanofilm interface from warmer regions to cooler regions due to the variation of surface tension with temperature. After determination that thermocapillary forces played a key role in the dynamics of this system, the second part of the thesis, Ch. 6 and Ch. 7, focused on the fabrication of mirco-optical devices. In particular, we fabricated and characterized mircolens arrays and optical waveguides.

Looking back at the complete body of work, there are several overarching themes and observations about this system which will be examined. In particular, we will discuss some of the lessons learned during determination of the instability mechanism in Sec. 8.1. Then, Sec. 8.2 contains a discussion of MicroAngelo as a thermocapillary sculpting fabrication technique and finally, in Sec. 8.3, we conclude with areas of improvement and future study.

8.1 Dominant Instability Mechanism: Thermocapillary Forces

As has been extensively detailed in Ch. 3, Ch. 4, and Ch. 5, the thermocapillary (TC) model best describes this experimental system. However, it is interesting to look at what this means for the other two proposed models. The surface charge (SC) model is a completely valid thin film instability that just doesn't apply to this experimental system. It seems there is no clear mechanism for interfacial charge accumulation in our experimental setup. However, intentional placement of charge at the interface could be achieved with an additional processing step under an electron beam or ion gun which would make the SC model very relevant. On the other hand, the acoustic phonon (AP) model is more problematic as there is no clear system which would correspond to this model. The assumption of phonon propagation and then coherent reflection off the interface of a molten film is a stringent one and it is not satisfied by this material system.

Conductive heat transfer through the nanofilm/air bilayer is what makes these experiments possible. We have found that these experiments required large, sustained thermal gradients which can be difficult to achieve due to thermal diffusion. As compared to other fields, such as electric fields, it is much more difficult to localize heat flux because the spread in conductivities between thermal conductors and insulators is much smaller than the corresponding spread between electrical conductors and insulators. In surmounting this difficulty, we found that even small absolute temperature drops can lead to enormous gradients, provided that the gap for the temperature drop is small enough. We also learned that in nanofilm experiments the incredibly large difference in scales between the largest and smallest component can lead to counter intuitive behavior. In this system, the small size of the low thermal conductivity layers means that even though the thick layers have much higher thermal conductivity, the total temperature drop across the macroscopically large, high thermal conductivity layers can be greater than the drop across the nanoscale, low thermal conductivity layers. This is very counter intuitive when transitioning from macroscopic systems where all the components are of approximately the same size. In these macroscopic systems, the temperature drop is usually strongly localized in the low thermal conductivity layers and the high thermal conductivity layers can typically be ignored when considering the heat transfer through the system. This lesson is highlighted by our finite element simulations of the temperature within the experimental setup presented in Fig. 5.2(c). If you were to use the nominal difference between the heater and chiller setpoints as the temperature drop across the nanofilm/air bilayer, then you would vastly overestimate the actual temperature drop.

The last major theme for my experimental instability investigations is that when comparing experimental data to the predictions of linear stability theory, it is crucial to extract the experimental data at the earliest possible times because linear stability is a perturbative technique. This will typically make the experiments much more difficult. In our case, we needed to do *in situ* observation of the instability with height deflections on the order of nanometers. However, it represents a significant improvement over previous experimental investigations in this system which were allowed to grow far outside the linear range where other effects like contact with the bounding plate and film depletion became important.

8.2 Thermocapillary Sculpting of Nanofilms: MicroAngelo

The use of thermocapillary forces to sculpt nanofilms through the MicroAngelo technique shows a great deal of promise for future study. While we focused specifically on polymer nanofilms in this thesis, this was for experimental convenience and not a restriction of the technique. Indeed, MicroAngelo is generalizable to basically any thin film due to the universality of surface tension. The only requirement is that the film be molten, but this is an engineering challenge, not a physical limitation. Especially now that we know the dominant physical mechanism driving the deformation, the design and fabrication of structures is an area ripe for joint exploration by experimental and numerical studies of the deformation process. We spent most of our time in the long wavelength regime where the vertical length scales were significantly smaller than the lateral ones because it allowed the easiest connection between theoretical predictions and experimental measurements. However, this assumption can be relaxed during fabrication and might also lead to the creation of novel features. Due to its reliance on surface tension, MicroAngelo creates smooth and rounded structures, which means that it can act as a complimentary technique to traditional lithographic techniques which typically produce flat, 2.5 D structures. Empirically, it appears that patterns with in-plane curvature, such as rings, are easier to fabricate than long, straight patterns.

8.3 Areas for Further Study and Improvement

There are a few immediate improvements that could be made to the fabricated microlens arrays and waveguides. For the microlenses, fabrication would have been somewhat easier with a lower chiller temperature. In the regime chosen for fabrication, the chiller setpoint was approximately equal to the glass transition temperature of the polymer. This could have potentially influenced the resulting lens topography during removal from the setup. With a lower chiller temperature, the lenses would have solidified faster and been less sensitive to the conditions during removal. For the waveguides, it would have been useful to introduce a slight bend in the waveguide to offset the input and output ports. This did not end up being extremely problematic, but it would have helped to reduce the effect of cladding modes and background scattered light.

In terms of general fabrication improvements with the current setup, removing the thermal paste between the silicon wafer and the aluminum heater holder from the setup is highly recommended. The thermal paste was originally designed to provide good thermal contact between the aluminum heater holder and the nanofilm substrate. Unfortunately, the thermal paste was highly non-Newtonian and was not amenable to precision dispensation. Even when we filled a mold in an attempt to control the amount of thermal paste, variable amounts of thermal paste were left on the mold depending on the speed, direction, and technique of removal. As the thermal conductivity of the paste is not very large, it could be beneficial to remove it completely and rely on the contact between the back surface of the substrate and the polished top surface of the aluminum holder. This would remove a major source of uncertainty in the fabrication process and hopefully improve the reproducibility of the fabrication.

The last major issue with this iteration of the experimental setup is that achieving parallelism to within nanometers over centimeters is very challenging. We tackled this issue by taking great care to use a level spin coater when making the spacers on the sapphire window. We made them photolithographically, but it would be interesting to fabricate them out of metal instead because they would probably have better structural properties. A more radical solution would be to remove the top plate to sidestep the issue completely. This would require a different heat transfer mechanism than pure conduction to create the necessary gradients, but would offer significant advantages during sample preparation.