Effect of Height of Nanochannels on Hydraulic Resistance and Water Evaporation

Sydney Dever-Mendenhall[1,2], Chu-Yao Chou[2], Chuanhua Duan[2]

Walt Whitman High School, 7100 Whittier Blvd, Bethesda, MD 20817[1], Boston University, 110 Cummington Mall, Boston, MA 02215[2]

BOSTON UNIVERSITY

Introduction

Water evaporation on the nanoscale is markedly different than water evaporation on the macroscale, though little is known about how this system works. Here, we investigate how hydraulic resistance (a measure of how impeded the flow of water is in a system) affects the evaporation rate and the meniscus size of water evaporating in a confined, kinetically-limited space. We also investigate how the size of the meniscus as compared to the contact angle, theta (the angle formed by the meniscus and the side of the nanochannel), affects the evaporation rate. The results of our research may be used for innovations in technology, specifically thermal management devices such as evaporative cooling devices and inkjet printing. To conduct this research, we etched nanochannels into Si chips, measured the evaporation rate from them, and compared the results with past literature data.

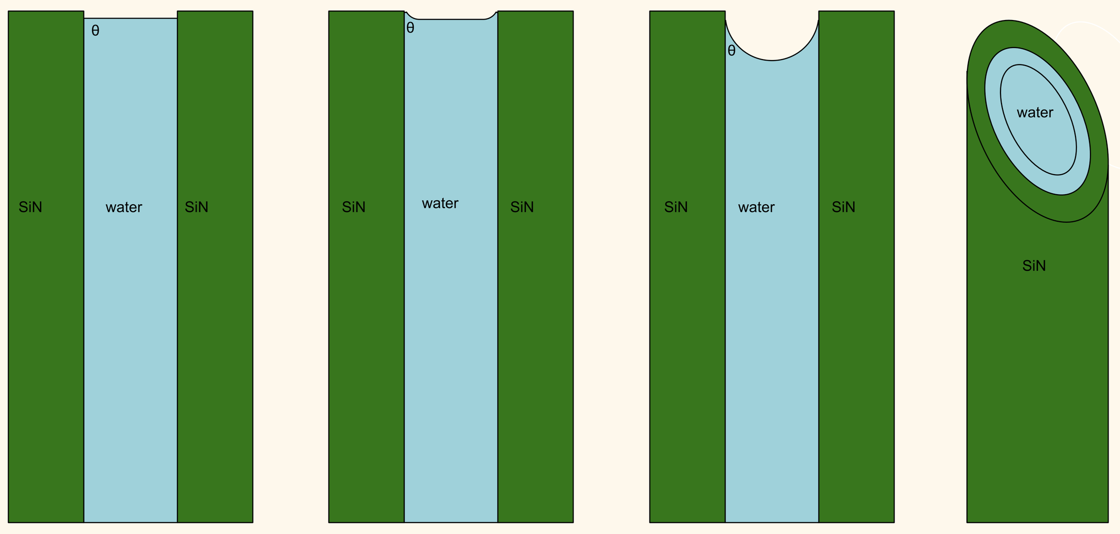


Figure 1. The nanochannels made from SiN are shown above. The contact angle, θ, changes based on the area of the meniscus. There is a higher ratio between the meniscus and θ when the meniscus is elongated. When the meniscus is flat, as in the image to the far left, the ratio is 100%.

Methods

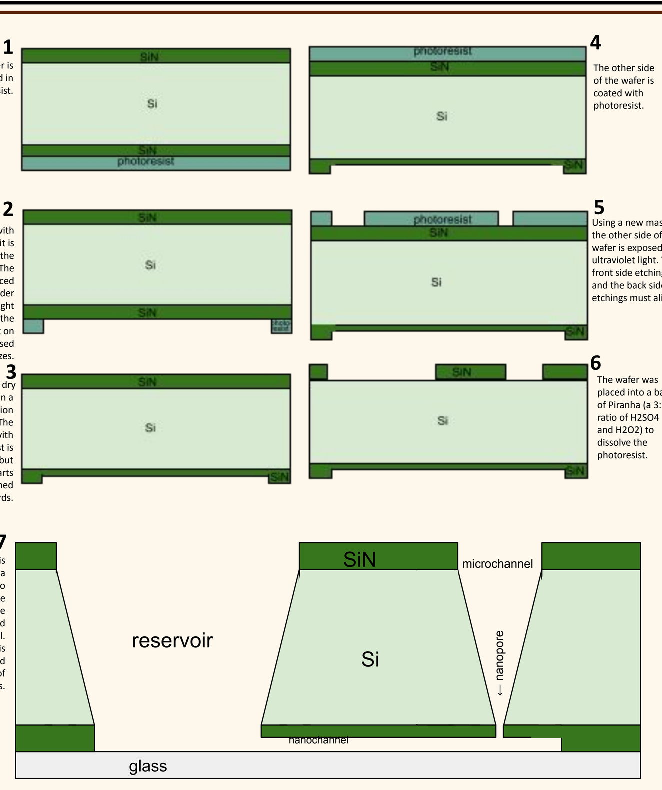


Figure 2. The first six steps taken to fabricate the Si chip (top) and the complete chip (bottom).

In order to run our experiments, we had to fabricate Si chips and etch nanochannels and reservoirs into them. We then drilled nanopores onto the chip using a focused ion beam (FIB) and bonded it to a piece of glass.

To observe the evaporation rate within the nanochannels, we placed the chip on an inverted microscope and filled the reservoirs with water. Once the water had completely filled the nanochannels, we used a vacuum to drain the nanochannel, recording the drying rate.

Figure 3. The Si chip. The large rectangles are the reservoirs, and the small rectangles are the membranes that the nanopores are drilled into.

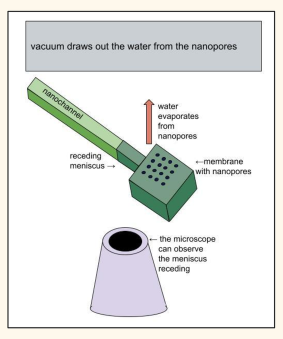


Figure 4. The experimental setup. The chip with the nanochannels on it is positioned above the inverted microscope on the stage of the inverted microscope. This is the experimental setup.

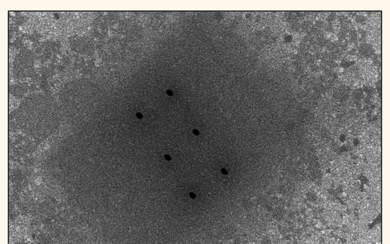


Figure 5. An example of nanopores drilled into the membrane of a chip.

Results

Using the inverted microscope, we were able to observe the meniscus receding inside the nanochannel as the water evaporated. The meniscus moved from left to right as the channel emptied.

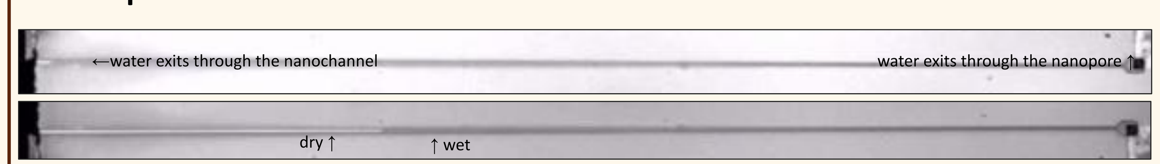


Figure 6. The channel drains and the meniscus recedes from left (top) to right (bottom) as the water evaporates.

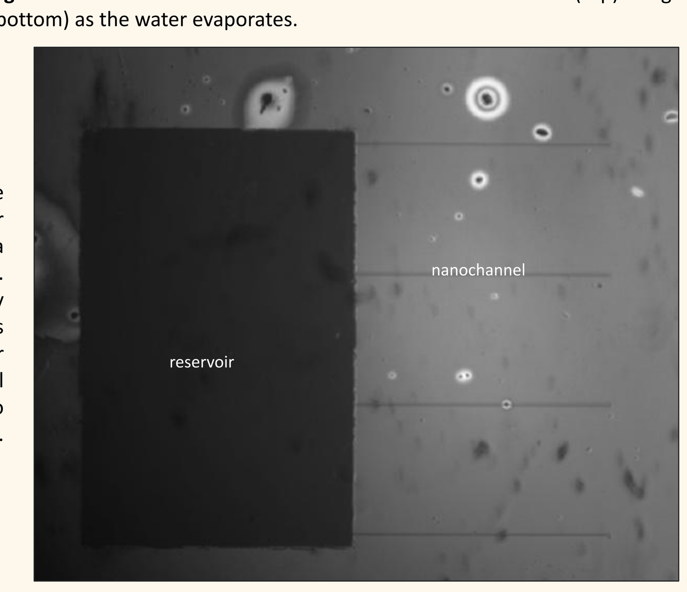
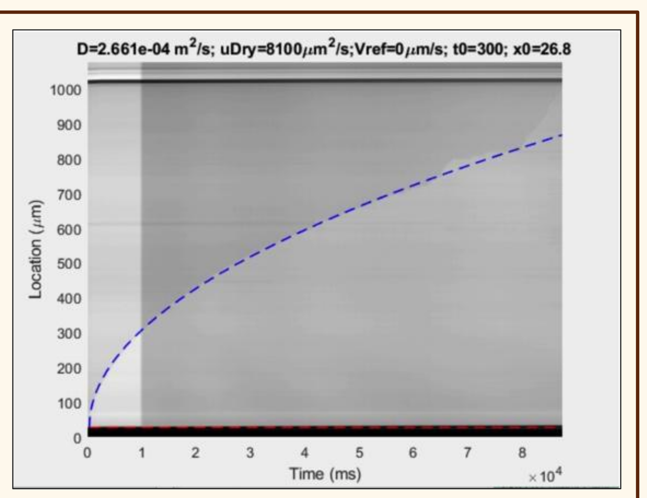
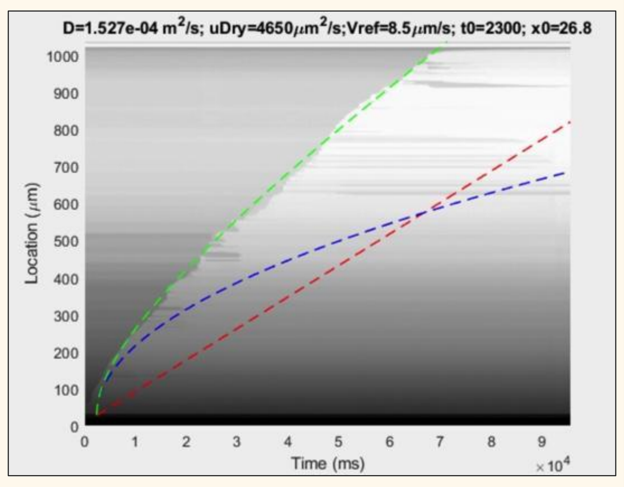


Figure 7. The Si chip under a microscope. Every reservoir has four nanochannel attached to it.

To calculate the drying rate through the nanopores, we first had to know what the drying rate was for a nanochannel without pores (a dead end channel). The drying rate of the dead-end channel is a square root function. The drying rate for a non-dead end channel is a composition of this square root function and a linear function.





Figures 8 & 9. The evaporation velocity or channels with pores (on the right) is a composition of the evaporation velocity of the dead end channel (on the left)and a linear function.

We found that the data comparing hydraulic resistance to evaporation rate scattered. We then examined the relationship between hydraulic resistance and meniscus size and found that a larger hydraulic resistance causes the surface area of the meniscus to expand. The longer channels had a higher hydraulic resistance, meaning that they had larger menisci.

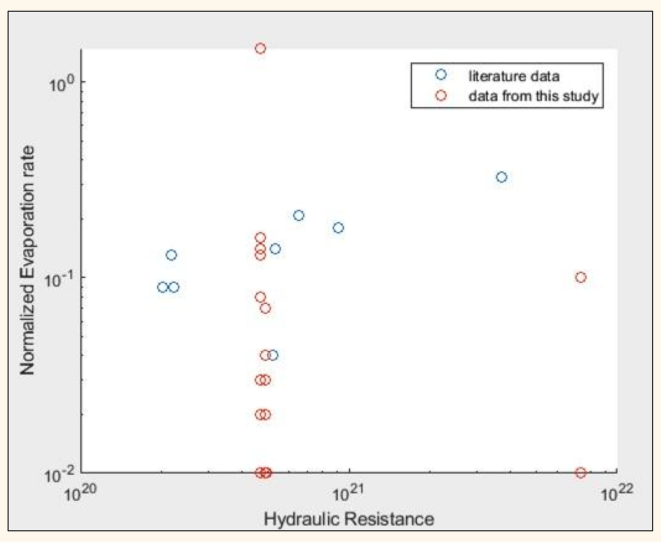
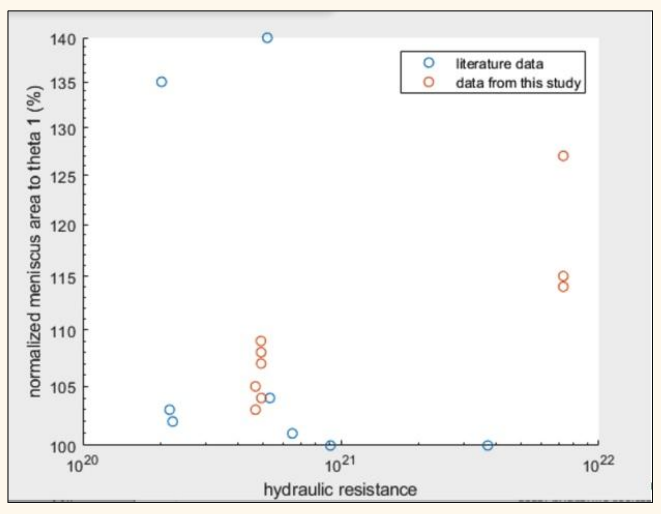


Figure 10. The graph of hydraulic resistance (Rt) to normalized evaporation velocity (to create a normalized value set, each datum is divided by the maximum value in the data set that it originated from).



Figures 11. The graph of hydraulic resistance to normalized meniscus area to theta 1. As hydraulic resistance increases, so does the area of the meniscus.

We found that as the normalized meniscus area to theta 1 approaches 100%, the evaporation rate increases. This means that the evaporation rate is most rapid when the meniscus is flat. We theorize that this is because the vapor has to travel through the nanopore when the meniscus is curved and therefore faces more resistance over time.

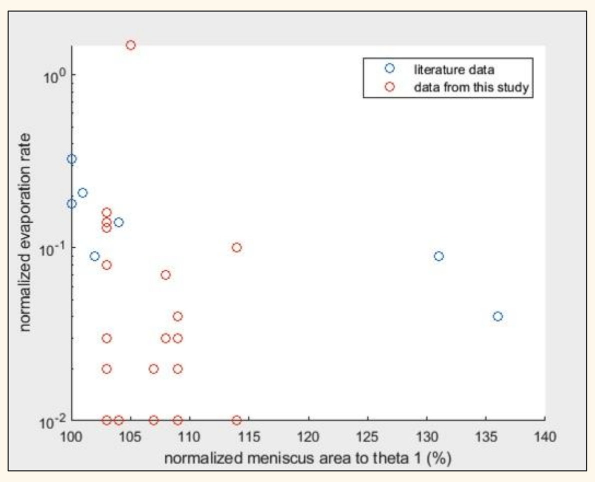


Figure 12. The graph of the normal meniscus area to theta ratio as compared to the normalized evaporation rate, where the evaporation rate is greatest when the normalized meniscus to theta 1 is 100%.

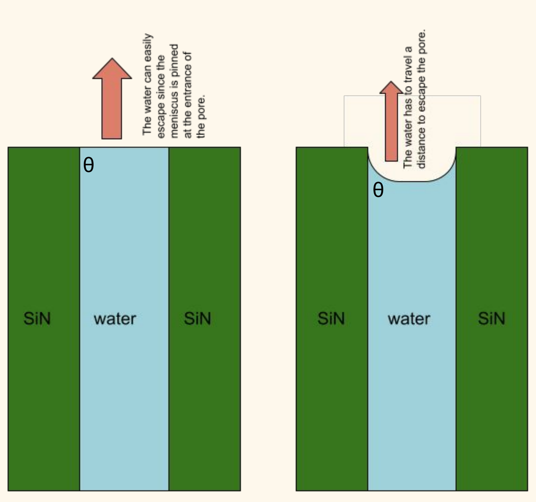


Figure 13. The water has to travel a greater distance when the meniscus is curved, meaning that it is more difficult for evaporation to occur. Therefore, the evaporation rate is slower when the meniscus is curved.

Conclusion

In conclusion, we fabricated nanodevices and measured the evaporation rate from them. We found that hydraulic resistance and normalized evaporation velocity have do not have a correlation, but that the channels with longer height have more hydraulic resistance. With this knowledge, we found that the hydraulic resistance and meniscus area have a positive correlation, and that drying rate and meniscus area have a negative correlation. This enables us to tune the evaporation rate by changing the hydraulic resistance. There is a negative correlation between meniscus area and evaporation rate, most likely due to the increased resistance water faces when traveling through a nanopore.

In order to better understand nanoscale fluid evaporation, more experiments should be conducted on the best way to tune the evaporation rate based on the hydraulic resistance. Future experiments could involve changing other variables, such as the number of nanopores or the temperature of the water, to see how they affect the evaporation rate of water.

References

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(2) Xie, Q.; Xiao, S.; Duan, C. Geometry-Dependent Drying in Dead-End Nanochannels. *Langmuir* 2017, *33* (34), 8395–8403. https://doi.org/10.1021/acs.langmuir.7b02027.

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