Capillary Condensation under Atomic-Scale Confinement

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Capillary condensation of water is ubiquitous in nature and technology. It routinely occurs in granular and porous media, can strongly alter such properties as adhesion, lubrication, friction and corrosion, and is important in many processes employed by microelectronics, pharmaceutical, food and other industries. The century-old Kelvin equation [1] commonly used to describe capillary condensation predicts that, under ambient humidity, water should spontaneously condense in capillaries with characteristic sizes less than a few nm [2-3]. However, the Kelvin equation has never been justified for this spatial scale experimentally and, in fact, is expected to break down in this case because the properties of water profoundly change under the strong confinement comparable to the diameter of water molecules. Here we take advantage of van der Waals assembly of two-dimensional crystals to create atomic-scale capillaries and study water condensation in this challenging but omnipresent regime involving sizes below a few nm. Our smallest capillaries are less than 4 Å in size and can accommodate only a single layer of water molecules. Surprisingly, the simple Kelvin equation using the surface tension and contact angle of bulk water is found to describe well the condensation in our strongly hydrophilic (mica) capillaries and remains qualitatively valid for weakly hydrophilic (graphite) ones. We show, however, that this agreement is somewhat fortuitous and can be attributed to elastic deformation of capillary walls, which suppresses giant oscillatory behavior expected because of commensurability between atomic-scale confinement and molecule sizes. Our work provides a much-needed basis for further understanding of capillary effects at extreme nanoscale.

References

[1] W. Thomson. Proc. R. Soc. Edinburgh 7(1870), 63-68.
[2] L. R. Fisher, R. A. Gamble, J. Middlehurst. Nature 290 (1981), 575-576.
[3] J. Zhong et al. J. Phys. Chem. Lett. 9(2018), 497-503.

Figures

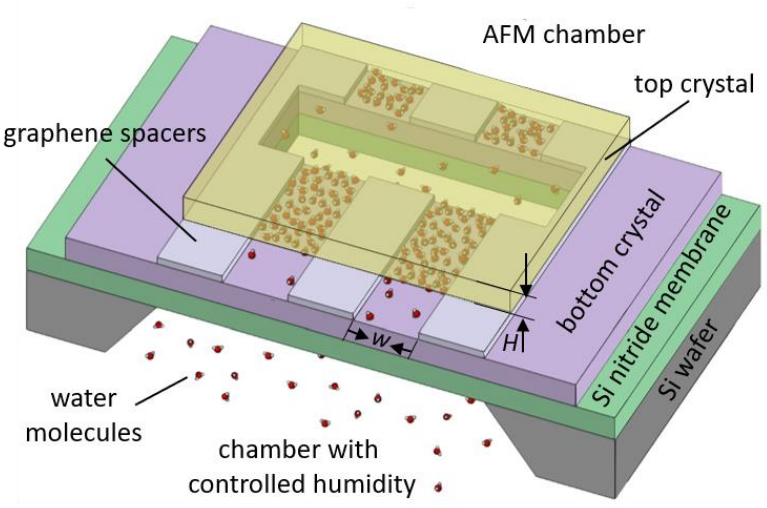

Figure 1: Schematics of the studied atomic-scale capillaries and water condensation inside