A MEMS Microtensiometer for Sensing Water Potential in Plants and Soils

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Principal Investigator: Abraham D. Stroock
Users: Michael Santiago-Pinero, Winston L. Black II, Siyu Zhu, Olivier Vincent, Antoine Robin

Affiliation: Department of Chemical and Biomolecular Engineering, Cornell University
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Contact: abe.stroock@cornell.edu, ms2343@cornell.edu, wlb62@cornell.edu, sz393@cornell.edu, robin.antoine93@gmail.com
Website: www.stroockgroup.org
Primary CNF Tools Used: Thermal oxide furnace, LPCVD furnace, Oxford 81/82, SÜSS SB8e, Oxford PECVD, DISCO dicing saw

Introduction:
We have been pursuing the application of the second generation micro-tensiometer in environmental and agricultural contexts and for the study of related fundamental phenomena. A micro-tensiometer (µTM) measures the temperature and water potential (equivalent to the chemical potential of water) in its immediate environment for applications in physical chemical research on the properties of liquid water.

We have reported the design of the second generation µTM, and the preliminary results about the response of embedded sensors in trees last year. This year, we focused on applying the µTM for monitoring the plant water status, and the study of metastable solid-liquid equilibrium of water. We have developed the methodology to install a µTM into the trunk of a tree, and conduct diurnal stem water potential measurements; the observed values agree well with the benchmark, manual technique. We have also managed to provide the first direct measurement of the Gibb-Thomson equilibrium between ice and liquid in the doubly metastable state of tension and supercooling.

Summary of Research:
Motivation. This project seeks to develop a microelectromechanical system (MEMS) tensiometer capable of sensing water potential. Water potential, Ψ (MPa) is a thermodynamic quantity that defines the thermodynamic availability of water for chemical reactions and physical processes such as mass transfer. Of particular interest is the range of Ψ near saturation that occurs in the plants and soil that make up the biosphere. Accurate, in situ measurements in this range have not been achievable with current technologies. The ability to perform such measurements has important implication for studying the basic biology of plants, for precision agricultural techniques such as deficit irrigation, and for basic questions about the thermodynamics of water itself.

Design. Figure 1 presents images of our microtensiometer. The top view shows the wiring associated with a strain gauge in the form of a Wheatstone bridge of poly(silicon) piezoresistors and a platinum resistance thermometer. The bottom view shows a cavity that we fill with pure liquid water; the layer of silicon above this cavity acts as a diaphragm, the deflection of which is measured by the strain gauge on the top side. This cavity is connected to the bottom edge via channels and a zone of nano-porous silicon that we form as a thin layer on the bottom side of the wafer; the design of this structure was inspired by the structure of xylem, the conductive tissue in plants. The cavity and microchannels are seal by bonding the bottom side of a glass wafer. As water leaves the cavity through the nanoporous membrane, the pressure of the liquid in the cavity drops until it comes to equilibrium with the external phase of water. We measure the difference in pressure between the inside and outside gives us Ψ and is measured with the calibrated strain gauge.
Method. Figure 2 presents an abbreviated representation of our process flow. The important steps in this process are: growth of insulating oxide (B2 thermal oxide furnace), deposition and patterning of poly(silicon) (LPCVD furnace C4), etching of cavity and microchannels (Oxford 81/82), anodic etching of porous silicon membrane, anodic bonding of silicon to glass (SÜSS SB8e), deposition and patterning of platinum with titanium adhesion layer, deposition of passivation layers (Oxford PECVD), and dicing. After dicing, chips were mounted and wire bonded to custom PCBs and selectively encapsulated in various materials to protect electronic elements from water and while allowing for exchange through the membrane.

Application in Plants. Figure 3 presents the comparison between the response of a µTM embedded directly within the stem of a potted apple tree (solid curve, right y-axis) and a Scholander pressure chamber (black circles, right y-axis). As expected, temperature (dashed curve, left y-axis) rises during the day and decreases at night, and the water potential decreases during the day after transpiration starts in response to sunrise, and increases when the transpiration slows down and the stem rehydrates with water feed from the soil. The measured stem water potential was within the range for a well-watered apple tree (> -15 bars), and matched the Scholander pressure chamber, a widely accepted hygrometer that requires point by point manual measurements and high-pressure gas.

Studies on Metastable Solid-Liquid Equilibrium of Water. Figure 4 presents the water potential of ice measured by direct submersion of a µTM inside ice and with cooling of the system down to -2.2°C. Figure 4A presents a schematic diagram of the direct contact between ice and metastable liquid water in the sensor. Figure 4B shows the linear correlation between the system temperature and measured water potential (MPa). The tension increases with the decreasing of temperature at the rate predicted by the Gibbs-Thomson relation (-1.2 MPa/°C).

Current Efforts:
We are building a mathematical model to predict the stem water potential in plants as a function of environmental parameters for comparison with the measurements. We would also like to proceed with the studies on the metastable solid-liquid equilibrium of water by improving the packaging of the sensor and the experiment set-up, or by modifying the design of the current generation of µTM to measure tension under lower temperature (i.e., -10°C or lower).