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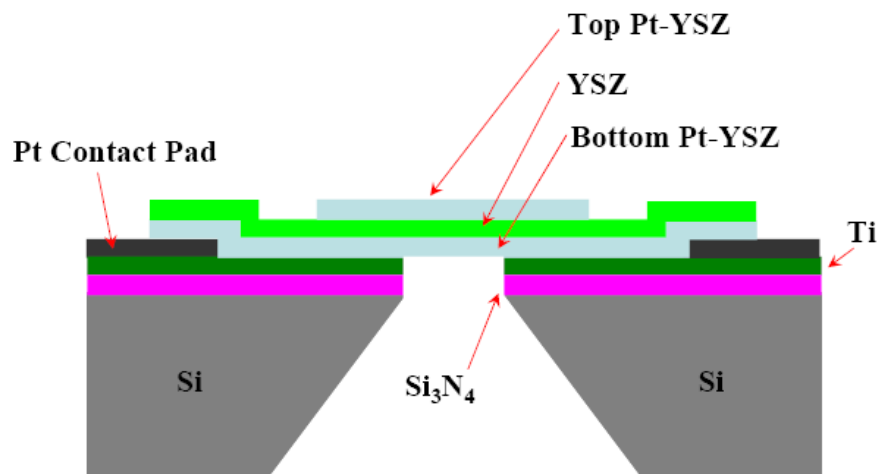
Numerical calculation of stresses and displacements on buckled square thin membranes with finite element method (FEM)

The goal of the project is to numerically calculate stress and displacement profiles of buckled square thin membranes. Estimation of extreme stresses is critical to design thermomechanically stable thin membrane structure. Previously, stress analysis was performed by energy minimization with von Karman non-linear plate theory, and membranes were released avoiding high stress regimes predicted by the energy minimization method (EMM) [1]. However, differences were observed between the EMM prediction and the experimental results, possibly due to the limitation of the EMM analysis. Improved analysis on stress and displacement is desirable to optimize the membrane structural design.

Design and fabrication of thermomechanically stable thin membranes were investigated for a portable microfabricated solid oxide fuel cell (μ SOFC). Fuel cells have been rigorously investigated as alternative power generation device in recent years due to their high efficiency and fuel versatility. However, their efficiency need to be still improved to produce more power, which is limited by the low voltage set by electrolytes, and the cost and heating start-up time should be reduced further. Microfabrication comes in as a solution to counteract these drawbacks imposed by SOFC characteristics. Thinning of the electrolyte physically decrease the travel length of oxygen ions, and thus increases the efficiency. In addition, the micro-scale can significantly reduce heating-up time and costs. As most of microfabrication processes are planar, the μ SOFC structure in our research work was designed to be a released tri-layer (anode, electrolyte, and cathode) planar membranes as shown in Figure 1. The electrolyte used was a sputtered yttria-stabilized zirconia (YSZ), and anode/cathode material was co-sputtered platinum and YSZ (Pt-YSZ). The μ SOFCs need to operate at high temperature (500-1000C), and released membranes expand with their four sides fixed. This behavior can cause high stresses inside the membranes, causing various failure modes including fracture, buckling, delamination, and cracking as shown in Figure 2. Thus, the design of thermomechanically stable membranes at high operation temperature was the key. After characterization of material properties, including residual stresses, Young's modulus, and coefficient of thermal expansion (CTE), extreme stresses were estimated with a set of geometrical conditions with EMM. Based on deflection pattern observation [2], the deflection profiles were modeled as a sum of symmetric deflection functions. The strain energy was calculated with von Karman non-linear plate theory, and minimized to obtain coefficient of the symmetry functions, and thus to estimate displacement and stress. Avoiding the high-stress regimes and producing larger power with smaller thickness and larger area, μ SOFCs were fabricated with the electrolyte as thin as \sim 150 nm in the post-buckling regime. Released membranes were thermally cycles several times up to 625C, slightly higher than the minimum operation temperature. The μ SOFCs with \sim 150-nm-

thick electrolyte layer successfully survived thermal cycles without fracture, but with permanent deformation as shown in Figure 3. Thinner membranes showed better thermomechanical stability because thinner membranes are easier to buckle, and can release stress with out-of-plane displacements. The EMM analysis confirmed this tendency. Thicker membranes (~250-nm-thick electrolyte) were predicted to be stable by EMM, but experimentally cracked and failed. Fabricated non-cracked but buckled membranes successfully produced the power. FEM analysis is necessary to have improved prediction of extreme stresses to optimize the design. Post-buckling region cannot be predicted well theoretically, and thus numerical simulation is critical.

In this project, a tool to predict stress and deflection profiles of square membranes with residual stresses will be developed. With this tool, optimized design of thermomechanically stable thin membrane structure (smaller thickness for improved efficiency and larger area for more power production) will be pursued. The result will be compared with the EMM and experimental results. This prediction will be also useful to confirm other testings, such as bulge test to obtain material properties of thin membranes.



[Not to scale]

Figure 1: Cross sectional view of the fuel cell device with electrical outputs.

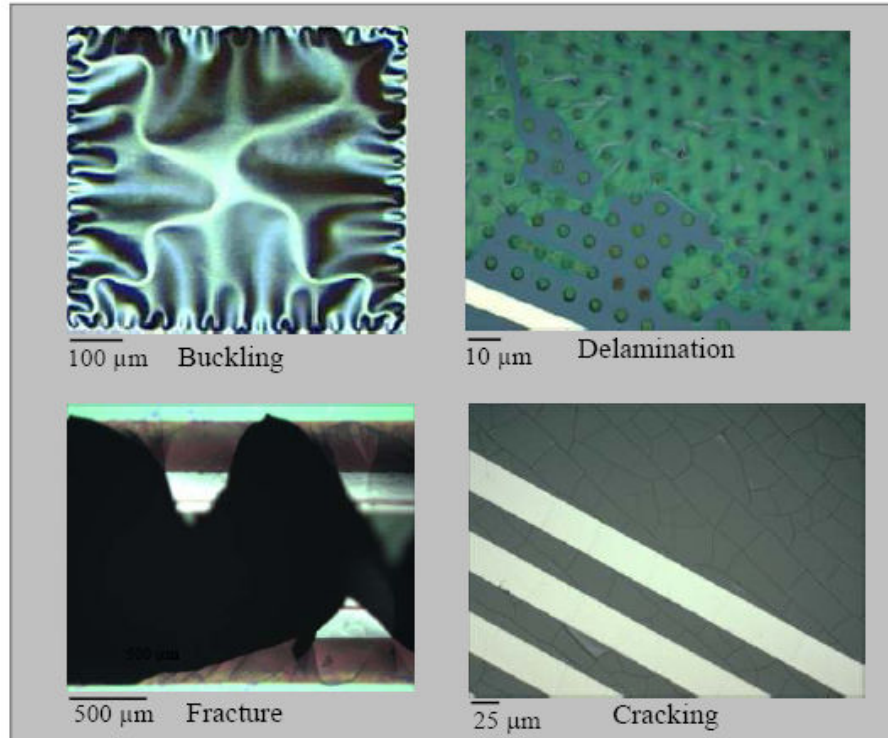


Figure 2: Failure modes of thin membranes

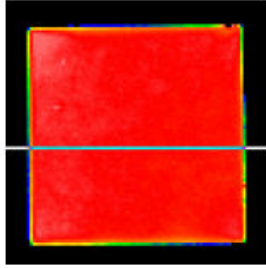
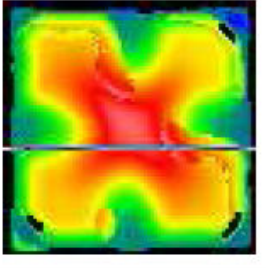
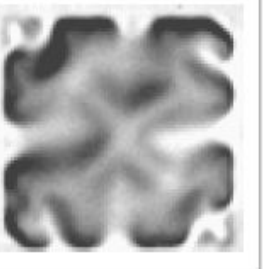
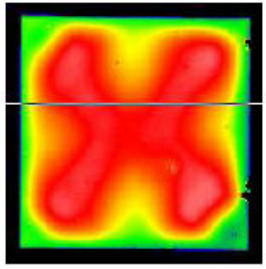
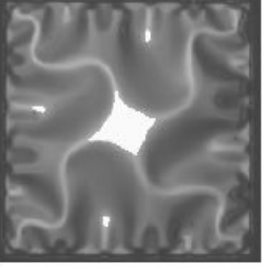
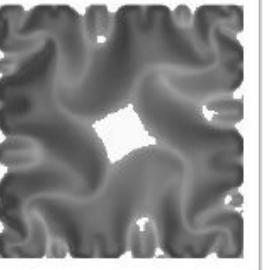
Cell Size	Before thermocycles	After 1 st heating to 625°C	After 2 nd heating to 625°C
Trilayer (~80μm)	Flat 	1 st buckling 	1 st buckling 
Trilayer (~180μm)	1 st buckling 	2 nd buckling 	2 nd buckling 

Figure 3: Fuel cell stack (~150-nm-thick electrolyte) buckling behaviors under thermocycles observed with Zygo surface profiler. All images taken at room temperature.

[1] N. Yamamoto, Thermomechanical Properties and Performances of Microfabricated Solid Oxide Fuel Cell (μ SOFC) Structures, Master's thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2006.

[2] V. Ziebart, O. Paul, and H. Baltes. Strongly buckled square micromachined membranes. *Journal of Microelectromechanical Systems*, 8:423–432, 1999.