Contribution ID: **50** Type: **Invited Oral**

Micro-Electromechanical Systems (MEMS) for extreme fusion environments

Wednesday 3 September 2025 09:30 (30 minutes)

This invited presentation highlights recent advances in developing Micro-Electromechanical Systems (MEMS) for the extreme environments of fusion reactors. There is a critical technological need for diagnosing wall conditions with high spatial and temporal accuracy within a Fusion Pilot Plant (FPP). MEMS encompass a wide range of micron-scale devices that seamlessly integrate mechanical and electrical components for high-sensitivity measurements and actuation. Collaborating with other leading institutions, Sandia National Laboratories is developing embedded, radiation-hardened MEMS sensors for in-situ monitoring of tungsten (W) armor erosion of plasma-facing components (PFC). The principal designs are MEMS devices embedded between the W armor and bulk tile material, such that an array of MEMS would provide local, in-situ, real-time thickness measurements as the armor erodes from the plasma-facing side. Two routes are explored: an ultrasonic MEMS device that propagates an acoustic wave (100kHz-10MHz) through the W via a high-temperature piezoelectric, and an optical interferometer that infers thickness via the resonant frequency of the W armor without the need for active electronics. First generation ultrasonic MEMS made of lithium niobate (LiNbO3) and aluminum nitride (AlN) have been fabricated and tested at Sandia. Frequency-domain thickness measurements of 6mm W samples have been demonstrated, with signal response matching that predicted by COMSOL modeling. First fabrication of silicon photonic crystals for optical MEMS has been conducted at Stanford University. Initial results show that the photonic crystals meet the criteria for a 'zero-length sensor' required to accurately measure the W resonant frequency, which is proportional to armor thickness. Fabrication processes are tailored to control the optical cavity dimensions within the photonic crystal to improve performance, enabling monolithic silicon sensors that are expected to withstand the extreme radiation environment.

Additionally, Sandia has fabricated a new generation of MEMS charge-exchange (CX) sensors with remotely activated shutters. These are palladium metal insulator semiconductor (Pd-MIS) sensors which provide a compact way to perform local CX neutral flux measurements. Next-generation sensors have been fabricated with variable gold overlayer thicknesses to provide coarse energy resolution. Actuating silicon MEMS shutters with displacements of 30μm at 2.8kHz were successfully demonstrated, and will incorporate a 10μm electroplated gold coating to extend sensor lifetime. These MEMS development efforts support an ongoing project with Oak Ridge National Laboratory to develop in-situ W PFC repair methods using additive manufacturing (AM) and remote handling technologies. Preparations are underway for real-time MEMS thickness measurements during an in-situ W deposition procedure using the AM test stand at Oak Ridge. Integration and testing at operating tokamak facilities is also envisioned. Through these collaborative efforts, MEMS technologies will be validated for use in future FPPs, providing spatially and temporally resolved diagnostic data that will enable operational efficiency, acceptable component lifetime, and successful fusion energy generation.

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Track Classification: Edge, divertor and PWI diagnostics