Thin Film Active Materials

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This presentation describes recent progress and future trends associated with the development and potential use of thin film active materials. Active materials exhibit energy coupling, such as between mechanical energy and electrical energy. Some of the widely recognized active materials include piezoelectric (electro-mechanical coupling), magnetostrictive (magneto-mechanical coupling), and shape memory alloys (thermomechanical phase transformation coupling). Much of the physical phenomena associated with bulk active materials are well known (e.g., Curie brothers, 1800s); however, this cannot be said about thin film active materials. Thin film active materials, defined by dimensions on the order of microns, represent a relatively new research topic still in its scientific infancy.

At small scales, physical coupling phenomena exist that are neither fully understood nor present in bulk active materials. Some of these unique phenomena include atomic coupling at the nano-scale regime and increased surface area-to-volume ratios, providing opportunities to construct structures previously unimaginable. These advantages, coupled with the fact that new active materials are being discovered (e.g., ferromagnetic shape memory alloys), suggest that active thin film material systems will be pervasive throughout our society in the upcoming decades. Some applications for exploiting these unique phenomena range from powerful solid-state actuators to miniaturized sensors or to clean power generation systems. This presentation provides a window into the possible future thin film active materials provide our society.

Research is being conducted on a wide range of active materials, including bulk and thin film in the Active Materials Lab at the University of California, Los Angeles (UCLA). One particular example is thin film shape memory alloy composed of Ni and Ti (thermo-mechanical coupled). This class of shape memory materials, discovered in bulk form in the 1960s, represents a benchmark material for shape memory alloys. While many other binary and ternary shape memory systems exist, NiTi is the most studied and well characterized. One of the first publications on thin film NiTi was in the early 1990s; therefore, research activities on thin film shape memory alloys is a relatively new topic. Shape memory materials undergo a solid phase transformation from a low temperature martensite phase to a relatively higher temperature austenite phase. The specific phase transformation temperature is tailored by altering the composition of the material.

One unique property associated with NiTi is the ability to recover (actuate) a specific shape when heated through the austenite phase. For example, imagine a NiTi wire bent in the lower temperature martensite phase. When heated (e.g., using Joule heating), the wire quickly returns to the original straight configuration (i.e., shape memory). This somewhat magical behavior is simply a phase transformation to a specific crystallographic arrangement resulting in "shape memory." This process converts thermal energy into mechanical energy and is used in a wide range of applications including vascular stents (biocompatible), electrical connectors, satellite release bolts, and coffee pot thermostats. While shape memory materials provide unique attributes, the bulk materials bandwidth (1 Hz) limits the material's applicability in many situations. The bandwidth limitation is due to the relatively slow cooling processes related to surface area-to-volume ratios. However, thin film shape memory materials have very large surface-to-volume ratios, allowing orders of magnitude higher bandwidths to be achieved.

Recent work at UCLA demonstrated thin film shape memory alloy bandwidths in excess of 100 Hz with theoretical predictions approaching the kHz regime. These large bandwidths, along with associated large stress and stain output, provide films producing enormous values of power per unit mass (i.e., 40 kW/kg). The relatively large specific power (compare to 100 W/kg for small motors) provides unique opportunities for small-scale applications (e.g., miniature motors and heart valves). One pump design on the order of centimeters is used to articulate the nose cone of a small missile system. In addition to this application, a pumping motor is useful in moving small amounts of fluids for various laboratory (lab on chip) and biomedical applications. One biomedical application uses the pump as an embeddable drug delivery system. Coupled with the appropriate sensors, this miniature (i.e., sub-millimeter) pump could replace a human pancreas in individuals suffering from diabetes. More recently, a cardiologist proposed using this material for a percutaneously placed heart valve. This revolutionary idea allows heart valve replacements without major surgery. Therefore, these and many other future applications exist for thin film shape memory materials.

While the discussion above elucidates the potential that thin film shape memory materials offer to the community, the potential for the general class of thin film active materials is substantially larger. In the thin film regime, atomic coupling can be also be used to enhance and improve the performance of active material systems. For example, using exchange coupling interaction, a phenomena not present in the macro-scale, magnetostrictive materials' response can be increased considerably. One advantage of magnetostrictive materials is remote actuation. While atomic coupling is one possible opportunity, a number of other submicron phenomena coupling exist to further improve and enhance thin film active materials. For example, newly developed multiferroic systems are transforming energies between multiple states as compared to the classical two-state systems. The multiple state energy transfer is useful in constructing new high fidelity sensors such as magnetometers once unimaginable or the potential to provide novel clean power generation systems (e.g., mechanical to electrical power or solar to electrical power) far superior to existing systems (e.g., solar cells). These advancements will certainly change the way our world operates and arguably will lead to many new scientific discoveries well over the next century.

This presentation describes a wide range of thin film active materials and some of the concepts currently being pursued by academic and industrial researchers. This review includes fabrication and applications for these new actuator and sensor systems in the small-scale system. One future possibility is the interaction of vast numbers of small-scale actuators massed together for a common goal, similar to ants interacting during gathering operations. Another future application suggests these small-scale systems are used to remove or possibly prevent blood clots, thereby preventing catastrophic strokes. A more distant future foresees even smaller scale systems interacting and joining together to form solid structures. This solid structure could be similar to a fluid liquid that becomes a solid, morphing into different defined shapes. The fact that material scientists already design materials at the atomic level arguably provides credibility to the suggestion that structures could be designed to interact and be built at the micron level.