The Search for Multifunctional Materials:

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Abstract:
This project focused on the development and exploration of multifunctional materials and the means to synthesize and characterize them. Bulk and thin film samples of La$_x$Sr$_{1-x}$MgO$_y$ (LSMO), YMoO$_4$ (YMO), and YMn$_2$O$_5$ (YMOZ) were synthesized and characterized. In addition to basic characterization techniques (XRD, SEM, EDS), a cryogenic system was designed, fabricated, and used to study electrical and magnetic properties as a function of temperature. The capacitance of the YMO and YMOZ thin film samples was measured as a function of temperature, and both showed capacitance increasing with temperature. LSMO showed a large change in conductivity with temperature, which results from a change in magnetic ordering occurring near 300 K. XRD and EDS showed that both the bulk and thin film samples were single phased and free from contamination.

Experimental:
Materials were synthesized by solid state and solution based techniques. Thin film samples were deposited using pulsed-laser deposition (PLD) see Fig. 3-7. The quality and physical properties of these materials were characterized using scanning electron microscopy (SEM), energy dispersive X-Ray spectroscopy (EDS), and X-Ray diffraction (XRD). Capacitance loss factor were measured for the multifunctional samples and resistivity of the magneto-resistant material was measured from room temperature to 75K using the cryo-system constructed for this project see Fig. 8 - 12. A Labview software control interface was also developed to control and automate the cryo-system (Fig. 10).

Introduction:
Multifunctional refers to materials that possess properties that allow them to perform more than one function in a device or materials where one class of properties is coupled to another class of properties. This definition includes a very wide array of materials. Many of these materials are interesting for their potential use in advanced devices or to help expand fundamental scientific understanding. The continued miniaturization of data storage and the nearing end of Moore’s law for silicon based devices are both motivating factors to explore multifunctional materials. Soon device dimensions will reach the point where they can no longer be made smaller because of physical and material limitations. At this point for devices to advance each device will need to fulfill more than one function. The materials studied in this project are of particular interest for ultra-high density data storage where improved data reading and writing are needed for further miniaturization. YMO and YMOZ are antiferromagnetic ferromagnetic multiferroics (AFM-FM). LSMO is a magneto-resistive ferromagnetic oxide (MRF-M). Multiferroics are materials that possess two or more of the three ‘ferroic’ orderings (ferromagnetic, ferroelectric, and ferroelastic) in some systems these orderings are also coupled. Magneto-resistive materials are those that exhibit a change in electrical resistance with the application of a magnetic field. Both of these material classes are very interesting because of the opportunities to exploit their properties for use in logic, data sensing (Fig. 1), and data storage (Fig. 2).

Results:
In this project a state-of-the-art electrical property measurement system was fabricated using inexpensive readily available starting materials. Parts were custom machined, when necessary, and then assembled by hand. The system was automated using GPIB cards and LabVIEW software. The system is fully functional and is now used routinely to measure capacitance, resistivity, and electrical resistivity with plans for adding additional measurement capabilities.

- The Proportional Integral Derivative (PID) algorithm was tuned for the system and was used to very precisely control the temperature stage during the measurements. The results of this procedure are shown in Fig. 13 and 14.
- Several different material systems were explored with a desired goal of finding multifunctional materials. Dielectric constant and resistivity are two important properties of the material measured in this study.
  - The capacitance of the YMoO$_4$ and YMn$_2$O$_5$ thin film samples was measured as a function of temperature at 10kHz. Both showed capacitance increasing with temperature.
  - LSMO showed a large change in conductivity with temperature this results from a change in magnetic ordering occurring near 300 K.

Conclusions and Future Work:
This project was very successful from the point of view of developing new multifunctional materials as well as from the point of view of developing a new materials characterization technique for the Nanostructured Materials Research Lab. The development and testing of the cryo-system is a very important step towards a robust materials characterization infrastructure and will aid in many different research projects and publications. This project will result in the first report of the properties of YMoO$_4$ grown by PLD. The data collection and knowledge gained from working with the materials in this project will be very useful in future research.
Future work will include many improvements and refinements to the cryo-system such as the addition of a sample stage with two diode sensors and two heaters to be used to measure thermoelectric power, addition of pressure gages, creation of a sample stage with spring loaded pressure gages to simplify the creation, integration of electrical control into the LabVIEW interface, and improvements to the LabVIEW control to include greater flexibility and automation of data collection. Future work will also include an in-depth study of YMn$_2$O$_5$ including substrate matching to achieve epitaxial growth, review capacitance measurements, atomic force microscopy, and transmission electron microscopy.

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