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Megagauss Magnetic Field Sensors based on Ag_2Te

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Introduction

Pulsed power machines capable of producing tremendous energy face various diagnostic and characterizing challenges. Such devices, which may produce 10 – 100MAs, have traditionally relied on Faraday rotation and Rogowski coil technology for time-varying current measurements. Faraday rotation requires a host of costly optical components, including fibers, polarizers, retarders, lasers, and detectors, as well as setup, alignment, and time-consuming post-processing to unwrap the time-dependent current signal. Rogowski coils face potential problems such as physical distortion to the sensor itself due to the tremendous strain caused by magnetically induced pressures, which is proportional to the magnetic field squared (B^2). Electrical breakdown in the intense field region is also a major concern. Other related challenges include, but are not limited to, bandwidth and inductance limitations and susceptibility issues related to electrical magnetic interference (EMI).

A unique alternative is to exploit silver chalcogenide materials as magnetic measurement sensors. Silver chalcogenides typically refer to alloys containing at least one Group-VI elements (ns^2np^4), AKA chalcogens, of the periodic table. Tellurium is an example of a Group-VI element. Silver chalcogenides, or more specifically Ag_2Te, have been shown to be very sensitive measurement devices capable of yielding highly accurate magnetic measurements[1]. The material's electrical resistance, which will be exploited in a novel application for measuring extremely high magnetic fields, displays a large linear increase with applied magnetic field without saturation.

This paper details the specific area of research, development, and results of advancing this previously unexplored material for direct applications in measuring megagauss fields. Methodology of depositing, configuring, and packaging the silver chalcogenides in millimeter-size probes consistent to the physical constraints of the pulse power device under investigation are discussed in subsequent sections. All fabrication, material deposition, and stoichiometric characterization of the material were facilitated by resources and expertise of the University of Nevada, Las Vegas.

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Sensor circuit strategies

The sensor material, Ag_2Te, is magnetoresistive. This intrinsic feature proved to be advantageous in developing a method of measuring the change of resistance, as a function of the applied external magnetic field. The method of transporting such a measurement from the experiment to data recording instruments was of particular interest.

Two promising strategies were investigated in this paper. By utilizing the sensor element in a resistor-capacitor (RC) timer circuit, such as the familiar 555 integrated circuit family variety, the output data would be represented as either a pulse length or frequency modulated optical output. Such an optical signal would then be converted back to electrical signal, recorded, and finally post processed to unravel the corresponding time-dependent magnetic field. In this method, the signal would be in essence a “phase-like” measurement and thereby would not suffer from amplitude, absolute measurement, or calibration issues relating to diagnostic interfaces. The other alternative was to use the sensor element as a terminator in a microwave transmission line. In this case, the change in reflected microwave radiation would represent a quantitative measurement of the magnetic field.

In any event, both methodologies seemed equally promising. Due to the capital equipment requirements of the microwave technique as well as experimental constraints and challenges imposed by possible explosive-driven pulse power devices, timer circuitry became the primary focus.

Sensor element fabrication

Four forms of Ag_2Te for sensor elements were explored: (1) melting into quartz capillaries, (2) using native crystals, (3) thin films on the outside of the capillaries, and (4) thin films on glass slides.

The native crystals were determined to possess too large of a cross section, giving rise to too low (~1ohm) of electrical resistances. Resistance values on this scale are not only out of the normal operating range of typical RC timing circuits, but would also represent excessive circuit loading, which causes the circuit element to overheat.

Several attempts to melt the Ag_2Te into very thin (~300 micron ID) capillaries, to provide reasonable resistances, were made. However, it was determined that the surface tension effects kept the Ag_2Te from coalescing into a fine wire. Thin films of Ag_2Te deposited on the capillary resulted in large resistances, but the very thin and narrow conduction path was prone to physical damage.

Work primarily focused on thin films on glass substrates. The resistance of a natural crystal ~1mm X 1mm X 3mm was on the order of 1 ohm. This meant that the thin films needed to be developed with thicknesses of ~ 1 micron to reach the minimum 100 ohm resistance values required by RC timing circuits.

Thin film preparation

The Polaron E5200 sputter coater (Figure 1) was used to deposit a layer of pure silver on the substrates. A convenient thickness was determined to be 100-600 nm (Figure 2). A sputter depth profile for the 3,000 seconds was performed on the Ag deposited substrates. Thus, the sputter rate was determined to be about 0.6 nm/sec to yield an Ag layer of about 300 nm thick to start.

Thickness and composition characterization measurements were performed at the Desert Research Institute’s X-ray Photoelectron Spectrometry Sputter Depth Profiling (XPS SDP) Facility (Figure 3).

Figure 1. Polaron E5200 Sputter Coater

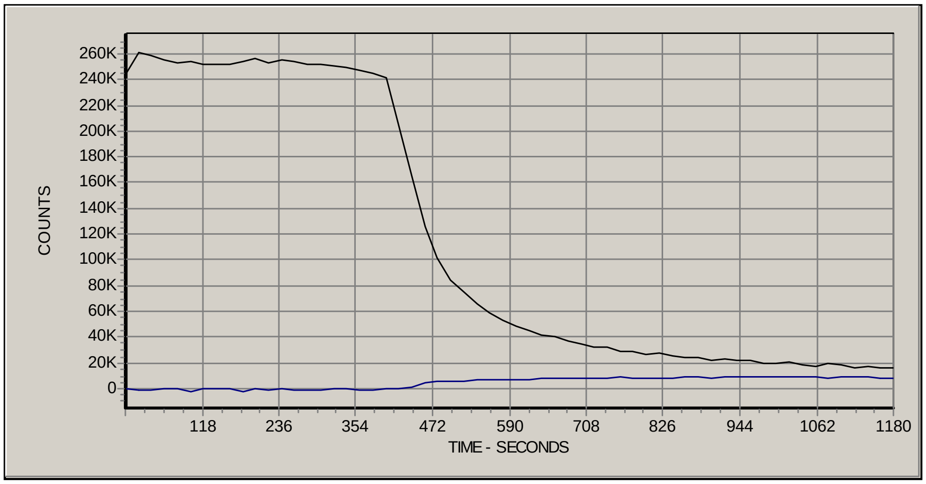


Figure 2. Sputter depth profile of Ag thin film substrate

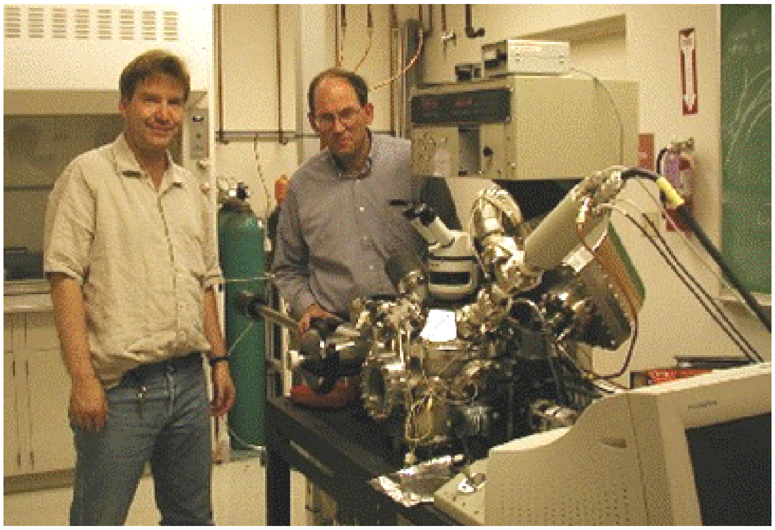


Figure 3. XPS SDP apparatus modeled by Doctors Allen Johnson and John Farley

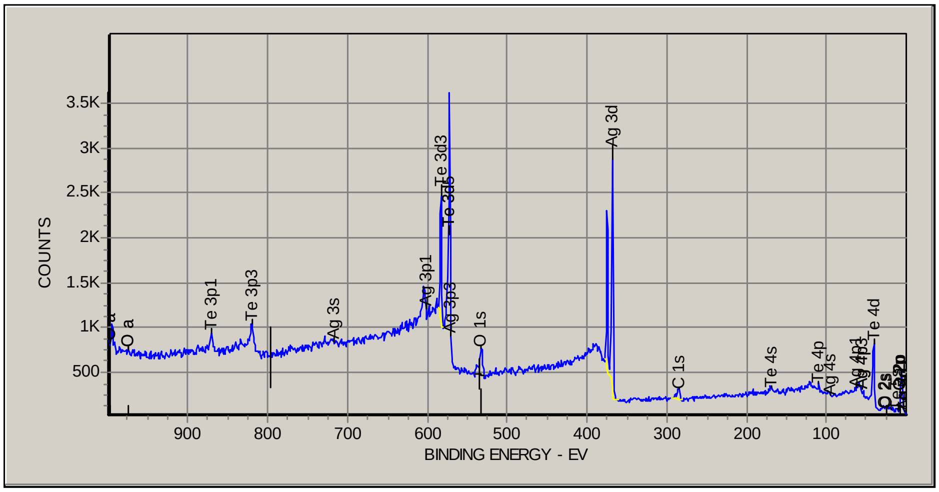
The silver layer was subsequently converted into the telluride by heating the silver film in an evacuated glass or quartz tube with elemental tellurium (Figure 4). Heating occurred in two stages: (1) At 200°C to form the telluride and (2) Heated at 300°C to create well-formed crystallites. The silver migrated on the substrate and did not form a film when the material was exposed to a much higher temperature. Heating the Te in vacuum formed a mirror film on the tube prior to introducing the silver. Presumably, this increased the surface area and vaporization/reaction rate. Previous researchers used a hydrogen stream to mobilize the tellurium. However, this method was rejected to due to safety risk and toxicity issues related to potential presence of H_2Te vapor.

Figure 4. Glove oven with thin-film Ag deposited substrates and Tellurium in vacuum-sealed quartz vessel

Once the Ag_2Te film was formed, Ag pads were deposited on each side of the substrate, thereby making an electrical connection with commercially available metal particle-loaded paint. Afterwards, the sensor area was covered with cellulose acetate-based lacquer (AKA nail polish) to guard against damage which made for a robust sensor element during circuit and transport properties evaluation.

Sensor element characterization

The Ag_2Te was chemically characterized at the Desert Research Institute's x-ray photon spectroscopy facility. The anticipated result was that of the expected 2:1 stoichiometric quantities illustrated in Figure 5. The main line is Ag 3d, and the smaller line is Si 2p, presumed to be that of the substrate constituent.



XPS Line	Adj'ed Be	FWHM	Area	Scans	Norm Area	Atom %
C 1s	284.596	4.031	600.544	1.000	299.804	28.288
Ag 3d	368.361	8.106	10233.919	1.000	297.892	28.107
Te 3d3	583.023	2.097	3265.566	1.000	159.003	15.003
O 1s	532.493	3.939	1513.587	1.000	303.144	28.603

Figure 5. Composition analysis of $AgTe_2$ material

The Ag_2Te layer was further characterized for its magneto resistance by introduction into a superconducting solenoid, which has a magnetic range of ± 9 Teslas (Figure 6).

Figure 6. Physical Property Measurement System

The thin-film deposited sensor achieved approximately 6 percent resistance change per Telsa (Figure 7). Resistivity was measured to be $\Delta\rho/\rho_o \approx 0.11(\Delta B/T)$ while a change in the electrical resistance, $\Delta R(B)/\Delta B$, was $\approx 5\Omega/T$.

This was expected to lead to an equivalent change in frequency in the timer circuit.

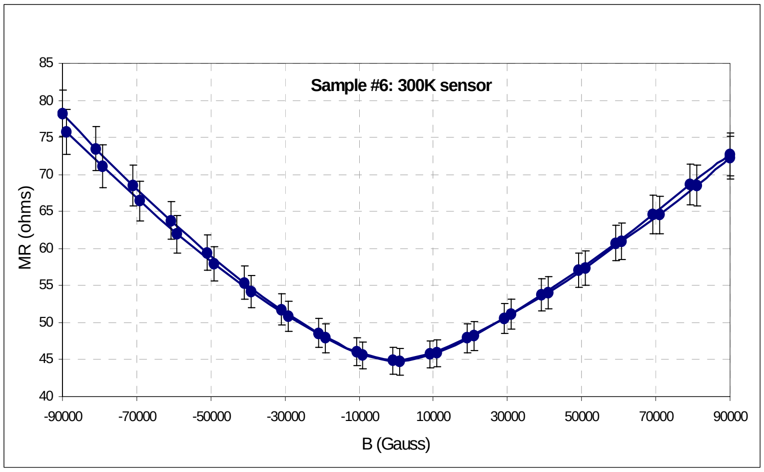


Figure 7. The Ag_2Te Sensor’s magneto resistance response to applied magnetic field

Sensor circuit issues

Surface mount timer circuits were the focus of attention; the smaller footprint of surface mount components allows smaller sensors to have higher spatial resolution and minimizes inductive loops. This attribute makes for a more robust behavior in time-varying magnetic fields. Our final surface mount device, the MIC1557, gives a square wave at several megahertz with just an external capacitor and the sensor element (Figure 8).

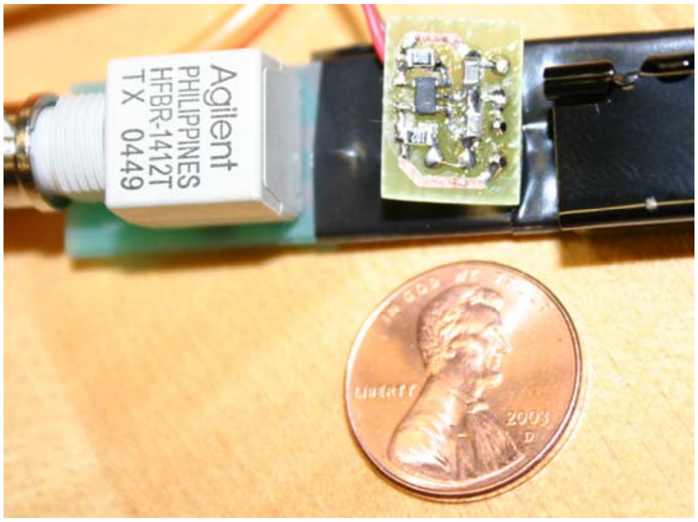


Figure 8. Surface mounted timer circuit with Ag_2Te sensor element

Also required are the electro-optic modulator (Figure 9) to transport the results to the data logging setup and power, which can either be a button cell battery or a large capacitor charged through a resistor, which would carry the load during an experiment.

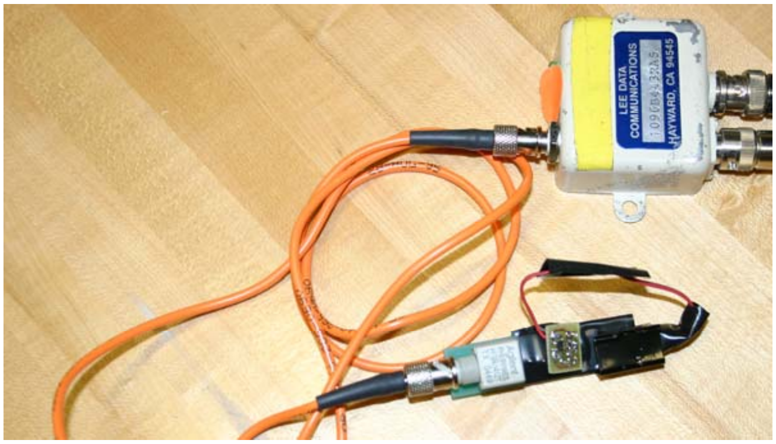


Figure 9. E-O and O-E transmitter and receiver with circuit

The final circuit produced an anticipated frequency response, dependent on a large external applied magnetic field, with time resolution of microseconds, (Figure 10).

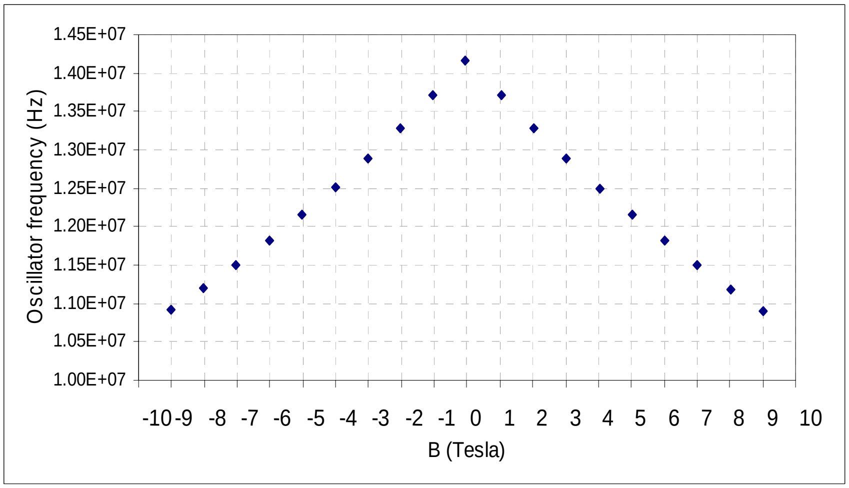


Figure 10. Frequency response to applied magnetic field

Conclusions

Given the scope of this project, the project team succeeded in developing a magneto resistive element via thin-film sputter deposition and demonstrated its response in an external high magnetic field. The team further explored cost-effective methods to transport a representation of the changing electrical resistance measurement, which are often made in a hostile environment, immune to EMI susceptibility-related issues.

Toward the end of this research, the associated process, procedures, and facilities improved greatly, thus producing sensors with reproducible results and qualities (Figure 11).

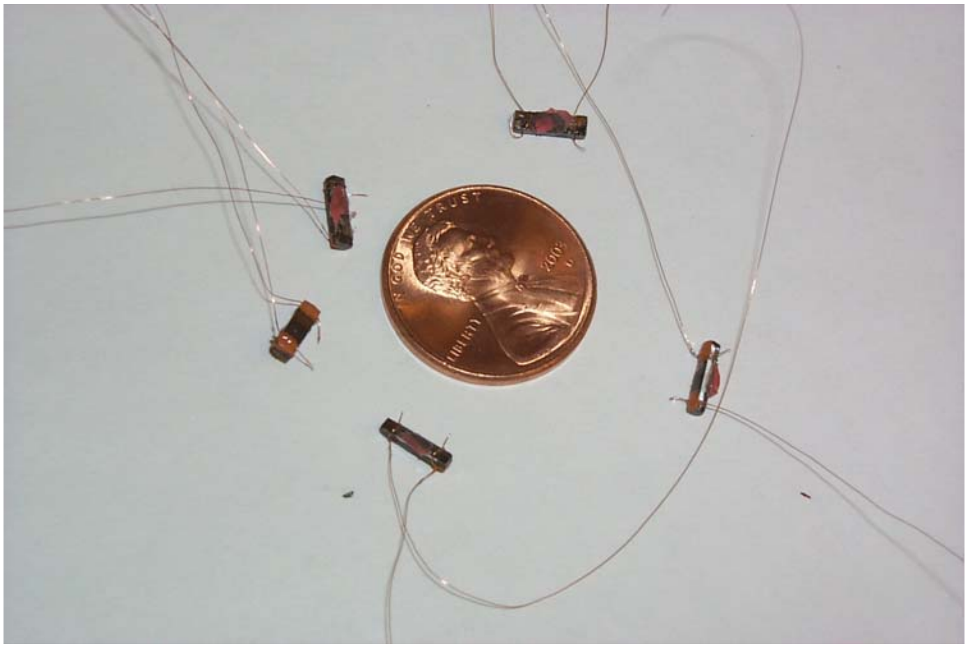


Figure 11. Final configuration of the last five Ag_2Te sensors produced. A “penny” reference is shown for scale

Existing NSTec and National Laboratory pulsed power machines (ATLAS, CYGNUS, DPF, explosive-driven pulse power, etc.) may benefit greatly by introducing these devices into existing suites. This would be especially true for explosive-driven sources in which costly diagnostics would be expended; these devices may be an ideal cost-effective alternative for essentially the same measurement.

Future work

These sensors were expected to be fielded in available pulsed-power devices configured to deliver >10T dynamic pulse. However, due to scheduling and availability constraints, the project team was unable to fulfill this goal.

As indicated earlier in this paper of the two strategies for measurement transport, exploring the material as an RF Loss Probe may also prove to be an effective measuring method. Bulk material as terminations/boundaries in microwave applications may exhibit field-dependent impedance changes, which may be very sensitive to reflection and transmission changes.

Other future applications include continued investigations and evaluations into the stoichiometric range and limits for optimal sensor constituents.

Acknowledgement

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[1] A. Husmann, J. B. Betts, G. S. Boebinger, A. Migliori, T. F. Rosenbaum, and M. L. Saboungi, MegaGauss Sensors, Nature,417, 421 (2002)