VersaLab®: A cryogen-free material characterization platform for quantum materials teaching labs

Introduction

We live in a technological world that is propelled by advanced materials research. This not only includes the well-known and historically significant semiconductors used in current CMOS-based conventional computers, but also next-generation quantum materials that will enable future functionalities. Quantum materials span a wide range of material classes, including topological insulators, 2D materials such as graphene, Weyl semimetals, etc. This list also includes high-temperature superconductors, which are often utilized in the burgeoning quantum sensing, quantum communication, and quantum computing realms.

Experimental teaching lab courses, in particular those devoted to material characterization, are in need of an update in order to keep up with the next generation of materials research. Typically, a given lab-based course experiment takes one of two forms. The first being a completely makeshift combination of various disparate, and often aged, components. The second is the highly polished commercial setup that is typically better suited for lecture-based demonstrations and are rarely able to perform more than one type of measurement. While both types of experimental setups do have a place as an educational tool, neither is particularly versatile nor adaptable to a wide range of materials characterization techniques.

The VersaLab provides an easy-to-use cryogen free measurement platform capable of measurements spanning 50-400 K and magnetic fields up to 3 tesla. As the name suggests, the VersaLab is incredibly versatile, enabling an industry standard suite of electric, thermal, and magnetic measurement capabilities in one easy-to-use instrument.

Educating future scientists who will be developing these next-generation quantum technologies is of paramount importance. What effort that exists currently is primarily performed at the advanced graduate and post-doc levels. In order to seriously address the one of the many goals laid out in the National Quantum Initiative Act **[1]**, namely that of "expanding the number of researchers, educators, and students with training in quantum information science and technology to develop a workforce pipeline", undergraduates should not be excluded from this effort **[2]**. Most students will move onto careers in industry, not academia, and would be best served by a curricula that provides a solid comprehensive hands-on experimental foundation. Whether it be at the undergraduate or graduate level, this is often lacking at many universities, in particular when it comes to utilizing industry-standard equipment. The VersaLab is an ideal platform perfectly suited for a modern experimental lab course capable as both an educational and research tool.

The VersaLab

Quantum Design's VersaLab **[3]** combines a research and teaching measurement platform for student laboratories primarily geared towards solid-state physics, physical chemistry, and material science. The VersaLab is a portable, cryogen-free cryocooler-based material characterization platform, that allows students to gain hands-on experience in materials characterization using an industry leading physical properties measurement system. With a base system temperature range of 50-400 K, this 3 tesla platform is perfect for accomplishing many types of materials characterization in a limited space, with no requirements for cryogenic liquids or high-power infrastructure.

Figure 1: VersaLab cryostat (left) and air-cooled compressor (right).

In addition to providing a variable temperature and magnetic field environment, the VersaLab enables several industry standard plug-and-play measurement options, including:

- Electric Transport (AC and DC):
  - van der Pauw-Hall
  - Sample rotation for anisotropic samples
  - High-pressure measurements
- Thermal:
  - Heat capacity
  - Thermal conductance and thermoelectric figure of merit (ZT)
- Magnetic:
  - Vibrating sample magnetometry (VSM) — up to 1000 K
  - First-order reversal curve (FORC) measurements
  - AC susceptibility
  - Broadband ferromagnetic resonance (FMR)

- Torque magnetometry
- High-pressure measurements

Additionally, with the LabVIEW®- and Python®-based application programming interfaces (APIs), one can also integrate third-party instruments for seamless customization.

Learning Outcomes

In addition to gaining hands-on experience and the practical skills necessary for performing cryogenic/high magnetic field measurements, students will fulfill numerous learning outcomes, most of which are directly related to the theoretical content from the classroom. Additionally, the VersaLab enables students to combine concepts in experimental design and methodology with data analysis and interpretation. More specifically, some examples of learning outcomes, sorted by measurement technique, include:

- **Electric Transport Learning Outcomes**:
  - Apply basic Ohm's Law principles to both 4-wire and 2-wire measurements
  - Learn the differences between DC and AC resistance measurements
  - Students will develop proficiency in techniques and considerations for wiring and mounting samples for electric transport measurements
  - Students will apply foundational knowledge of relevant solid-state physics to resistance vs. temperature and resistance vs. field characterization
- **Heat Capacity Learning Outcomes**:
  - Apply foundational knowledge of relevant solid-state physics to heat capacity measurements
  - Students will gain experience with small sample handling
  - Students will directly observe and measure the differences between first- and second-order phase transitions
- **Vibrating Sample Magnetometry Learning Outcomes**:
  - Apply the fundamental concept of magnetic induction and Faraday's law to magnetometry
  - Students will apply foundational knowledge of relevant solid-state physics to magnetic moment vs. temperature and moment vs. field characterization
  - Students will become familiar with concept of magnetic hysteresis
  - Students will develop proficiency in techniques for optimal mounting of samples for magnetic measurements to minimize instrumental artifacts

Measurement Examples

The magnetic field and temperature range accessible by the VersaLab, in conjunction with the numerous plug-and-play measurement options, enable the study of a wide range of technologically useful and fundamentally interesting materials, including:

- Semiconductors
- Magnetic materials (bulk, thin film, and nanoscale)
    - Ferromagnets, antiferromagnets, ferrimagnets
    - Magnetic recording media
    - Spintronic materials
- Quantum materials, *e.g.* high temperature superconductors
- Magnetocalorics
- Thermoelectrics
- Photovoltaics

The following three examples provide a broad representative survey of the types of measurements and materials suitable for a VersaLab-based lab course.

Hall Effect: GaAs-2D Electron Gas (2DEG)

Measuring the Hall effect of metals and doped semiconductors is one of the most common experiments performed in lab-based physics courses. The VersaLab enables measuring the Hall effect at higher fields and lower temperatures than are commonly available in an educational setting. Figure 2 (A) demonstrates the transverse Hall resistance (black) and longitudinal sheet resistance (red) of a GaAs-2DEG measured at 50 K spanning the full ±3 tesla field range of the VersaLab. The transverse Hall resistance shows the expected linear behavior with field, and the negative slope indicates electrons are the dominant charge carriers. Additionally, the longitudinal sheet resistance shows a significant parabolic magnetoresistance, also consistent with magnetotransport in a 2D electron system.

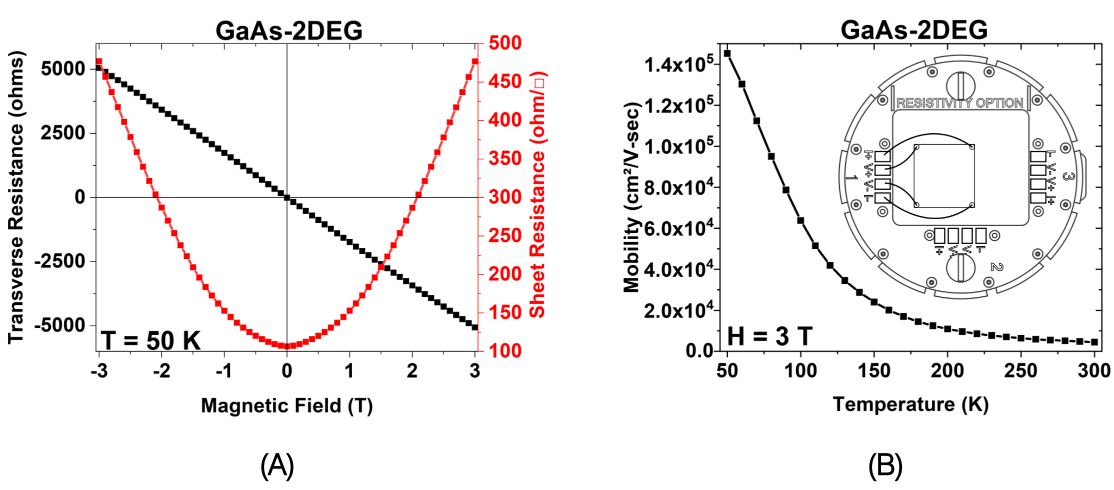


*Figure 2: **(A)** Transverse resistance (black) and longitudinal sheet resistance (red) measured at 50 K spanning ±3 tesla of a GaAs-2DEG. **(B)** Temperature dependence of the mobility. The insets show the van der Pauw measurement geometry.*

These measurements utilize the van der Pauw measurement geometry, where small electrical contacts are made at the outer boundary, *e.g.* corners, of the sample (Figure 2 (B), inset) and the current/voltage connections can be permutated with an external switching controller (Figure 3). The van der Pauw method enables one to measure the electrical resistivity and Hall effect in arbitrarily shaped samples as long as they are of a uniform thickness and contain no holes. Generally, this technique is utilized as it does not require precise geometric measurements to obtain accurate intrinsic material properties that commonly plague more conventional 4-point (*i.e.*, Kelvin) techniques. The carrier mobility can then be calculated from measurements of the Hall coefficient and sheet resistance. Mobility is an important fundamental material metric as it ultimately determines device speed, power efficiency, and current capacity. The temperature dependence of the mobility is shown in Figure 2 (B).

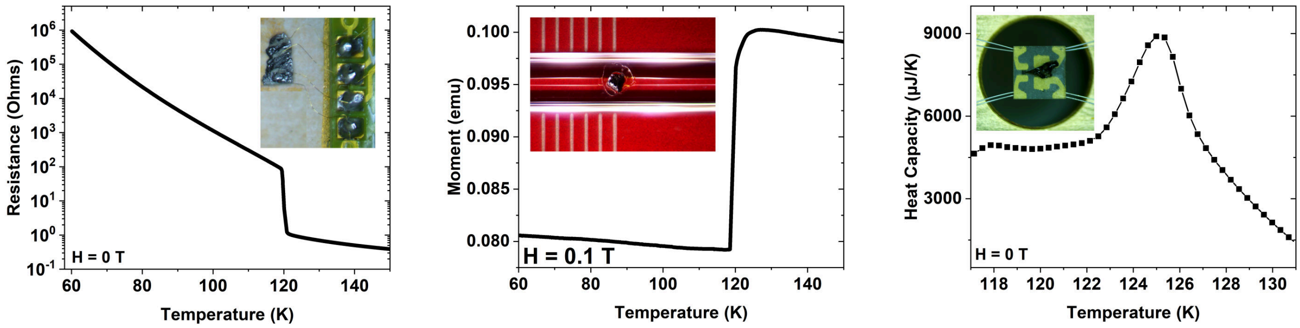
The VersaLab enables the students to not only perform but significantly expand upon the canonical Hall effect experiment by greatly widening the available temperature/magnetic field parameter space. Additionally, the van der Pauw measurement geometry and switching controller introduce advanced concepts often used in industry.

Figure 3: The van der Pauw-Hall Option switching controller automatically performs permutations of the current and voltage leads and collects the data required for calculation of carrier concentration and sheet resistance for a uniformly thick sample of arbitrary shape.

Phase Transitions: Magnetite

Understanding the origins and underlying physical mechanisms that govern the numerous types of phase transitions that can occur in a given material is ubiquitous in materials research. Examples of phase transitions that are readily measurable using the VersaLab include the ferromagnetic ↔ paramagnetic, superconducting ↔ normal, and metal ↔ insulator transitions. The Verwey transition temperature ($T_V \sim 120\ \mathrm{K}$) of magnetite (Fe_3O_4) is perfectly suited for the temperature range accessible with the VersaLab. Furthermore, magnetite is a naturally occurring mineral that can be easily and cheaply procured.

The first metal ↔ insulator transition was observed in the 1940's in magnetite. Figure 4 (A) shows the temperature dependence of the resistance, note the log scale on the *y*-axis. Figure 4 (A) (inset) shows the sample wired in the conventional 4-point Kelvin geometry. For temperatures above 120 K the resistance is relatively low consistent with a metal. As temperature is decreased a sharp increase in resistance is found (~2 orders of magnitude) near 120 K, indicating the Verwey transition temperature and the crossover to an insulator.



(A) (B) (C)

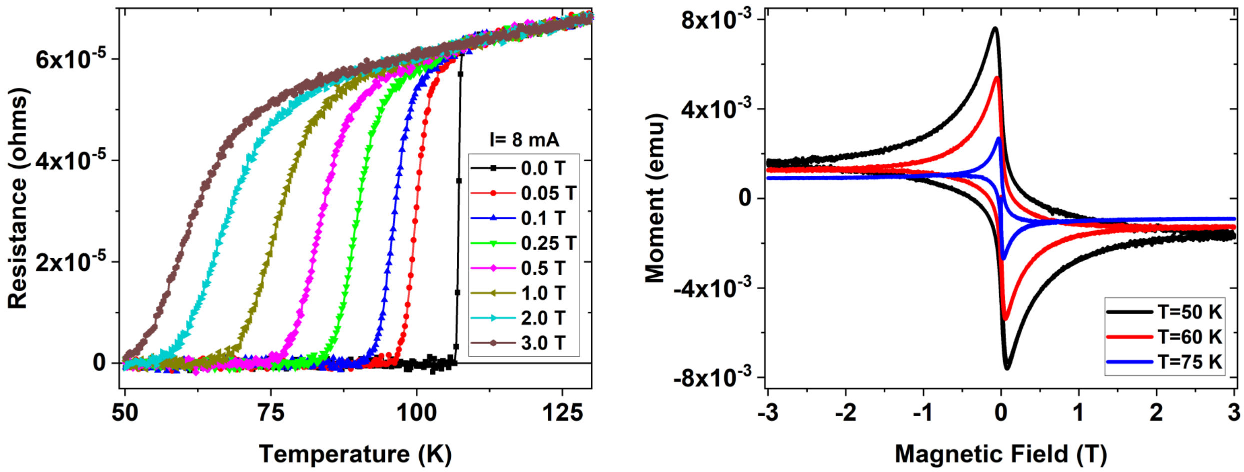
Figure 4: ***(A)*** *Resistance as a function of temperature measured with the ETO.* ***(B)*** *Magnetic moment as a function of temperature measured with the VSM.* ***(C)*** *Heat capacity measured as a function of temperature measured with the Heat Capacity Option. The Verwey transition temperature is clearly observed in each measurement. The figure insets show the mounted samples for each measurement.*

Correlating numerous measurement techniques is often required to fully understand the underlying properties of a given material. The VersaLab provides such a diverse toolbox. For example, the magnetic properties of the sample can be measured with the VSM, Figure 4 (B). Figure 4 (B) (inset) shows the mounted sample, which is simply glued to a quartz paddle sample holder with rubber cement. A clear drop in the field-cooled magnetic moment is observed as temperature is decreased through T_V, indicating a change in the magnetic anisotropy. Similarly, a peak is observed in the heat capacity, Figure 4 (C), another clear sign of a phase transition.

The multiple measurement options enabled by the VersaLab allow the students to probe many different aspects of a given phase transition to gain a full understanding of the mechanisms at play.

Quantum Materials: High T_C Superconductor

Superconductors are a prime example of a class of a quantum material that is used extensively for quantum sensing, quantum communication, and as a key component in the construction of many quantum computers. Understanding the temperature and magnetic field dependence of the superconducting transition temperature (T_c) is a critical first step in benchmarking their performance and potential utility. The resistance as a function of temperature for a bismuth strontium calcium copper oxide (BSCCO) superconductor with a zero field T_c of approximately 105 K is shown in Figure 5 (A) (black squares). Subsequent measurements at larger applied magnetic fields, up to 3 tesla, show a broadening and overall suppression of T_c. Similarly, the field dependence of the magnetic moment, Figure 5 (B), measured at a fixed temperature provides additional insight into the superconducting behavior.



(A) (B)

Figure 5: (A) Resistance as a function of temperature highlighting the suppression of the superconducting transition temperature as the applied field is increased. (B) Magnetic moment as a function of applied magnetic field highlighting the temperature dependence of the critical field.

Discovery Teaching Labs Initiative

The VersaLab is the flagship instrument within the Discovery Teaching Lab (DTL) Initiative **[4]**, which seeks to partner colleges and universities with leading technology companies to develop new curricula emphasizing hands-on experiential learning. By introducing industry-standard research instruments, students are inspired to "take theory into practice," thereby better training themselves to be successful in the next stage of their scientific careers. More specifically the goals are to:

- Increase career potential through more robust science education.
- Enhance curricula by providing hands-on instrumentation.
- Accelerate the development of future scientists, leading to research and technological innovation.

Over 10 experimental modules highlighting electrical, thermal, and magnetic measurements using the VersaLab are freely available from the Discovery Teaching Lab website. There are currently six institutions who are official partners within the DTL framework, Figure 6, and many more that use the educational modules and the VersaLab in their teaching lab curricula worldwide.

Figure 6: Academic partners in the Discovery Teaching Lab initiative.

Summary

The VersaLab is an easy-to-use industry-standard cryogenic measurement platform that has a proven track record as both a research and educational tool. Students gain experience with the fundamentals of safely performing measurements at cryogenic temperatures and high-magnetic fields. Additionally, the over 10 plug-and-play measurement options expose students to the diverse range of measurements commonly used by condensed matter physics and materials scientists, as demonstrated in the examples above. Instructors are free to incorporate the existing education modules within their curricula and are encouraged to also create their own for inclusion and dissemination on the DTL website.

References

[1] https://www.congress.gov/bill/115th-congress/house-bill/6227/text

[2] https://arxiv.org/abs/2109.13850v2

[3] https://qdusa.com/products/versalab.html

[4] https://discoveryteachinglabs.com/