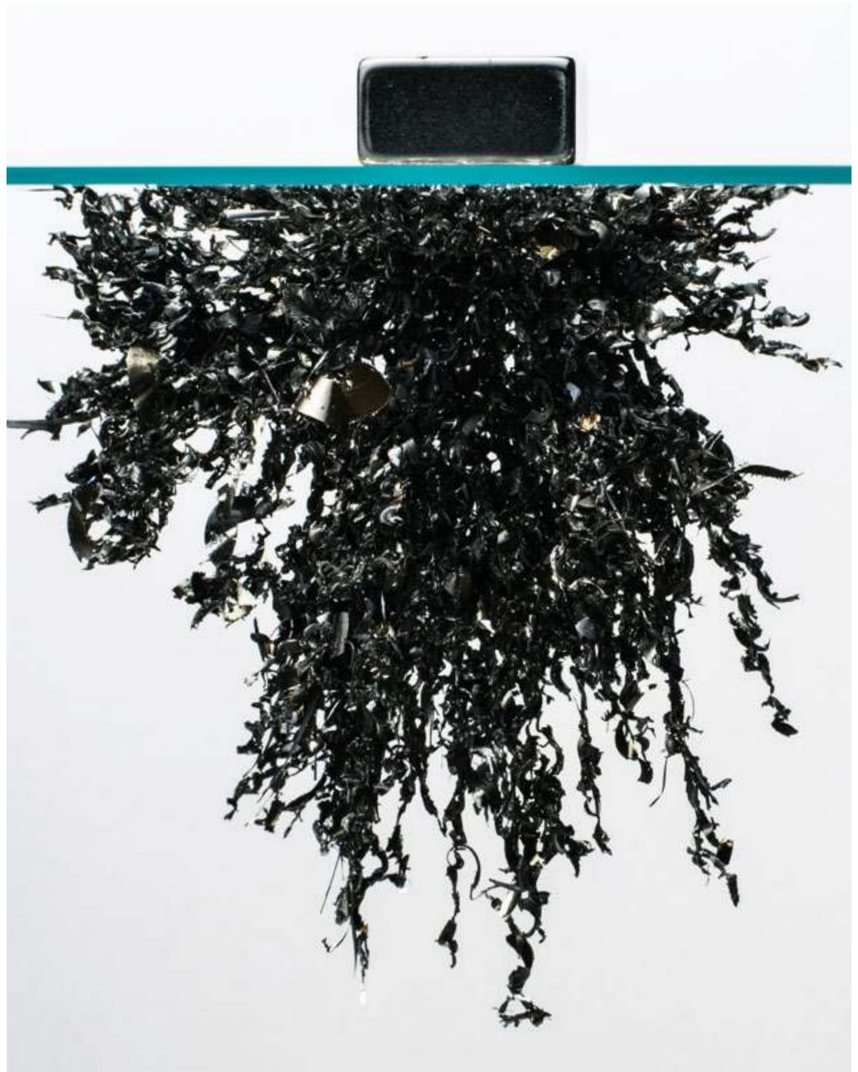
Pushing the boundaries – interrogating magnetism at material interfaces

In order to keep improving electronic devices, whether it be computers or sensors, researchers must understand what is going on, on an atomic level. Understanding the behaviour of ions within materials is difficult enough, but when you put two materials together it gets much more complicated. ***Dr Mikel Holcomb****, Associate Professor from West Virginia University, has dedicated her work to finding out exactly what happens at these boundaries.*



Magnetism is extremely important to our everyday lives. Without it, we would not have computers, credit cards, or the inevitable fridge magnets, to name a few. But our understanding of magnetism remains limited. When a material that is normally magnetic becomes too thin, or even at the boundary between two different materials, the magnetic properties can be lost – and this area of physics is not very well understood.

Dr Mikel Holcomb, from West Virginia University, has dedicated her career to better understanding magnetism, specifically looking at one interesting class of materials, complex oxides. A complex oxide is any compound that contains oxygen along with typically at least two other elements. They make up some of the most abundant minerals on Earth, and complex oxides show a huge variety of interesting properties, from superconductivity to dielectrics.

In particular, Dr Holcomb's group (and many collaborators including Romero, LeBeau, Stanescu and several national facility scientists) has made progress looking into thin films of a particular complex oxide called lanthanum strontium manganite, or LSMO. LSMO is an important material because it has the potential to be used in a variety of applications, including computers and sensors. It exhibits a range of interesting properties, including ferromagnetism – when a material maintains its magnetism even after a magnetic field has been removed. Dr Holcomb has developed and combined new methods to study the interfaces of these thin films, with an aim to learn more about magnetism and other types of interface properties.

The lab team: (from left to right) Navid Mottaghi, Justin Bowman, Professor Holcomb, Saeed Yousefi, Rob Trappen, Ghadendra Bhandari, Jonathan Cramer, Shalini Kumari. Not shown: Guerau Cabrera, Chih-Yeh Huang, Madelene Blackwell, Brandon Howard, Liam Mcgoldrick, Troy Williams, Viraat Das.

WHY INTERFACES?

In thin films in general, the properties at the boundary of two materials are often extremely different from the bulk of the materials. Many devices use boundaries, which can be the surface of a material – the boundary between it and the air – or the interface between layers of two different materials. This is because many properties like spin, charge, and orbital degrees of freedom, depend on the ions' surroundings within a material.

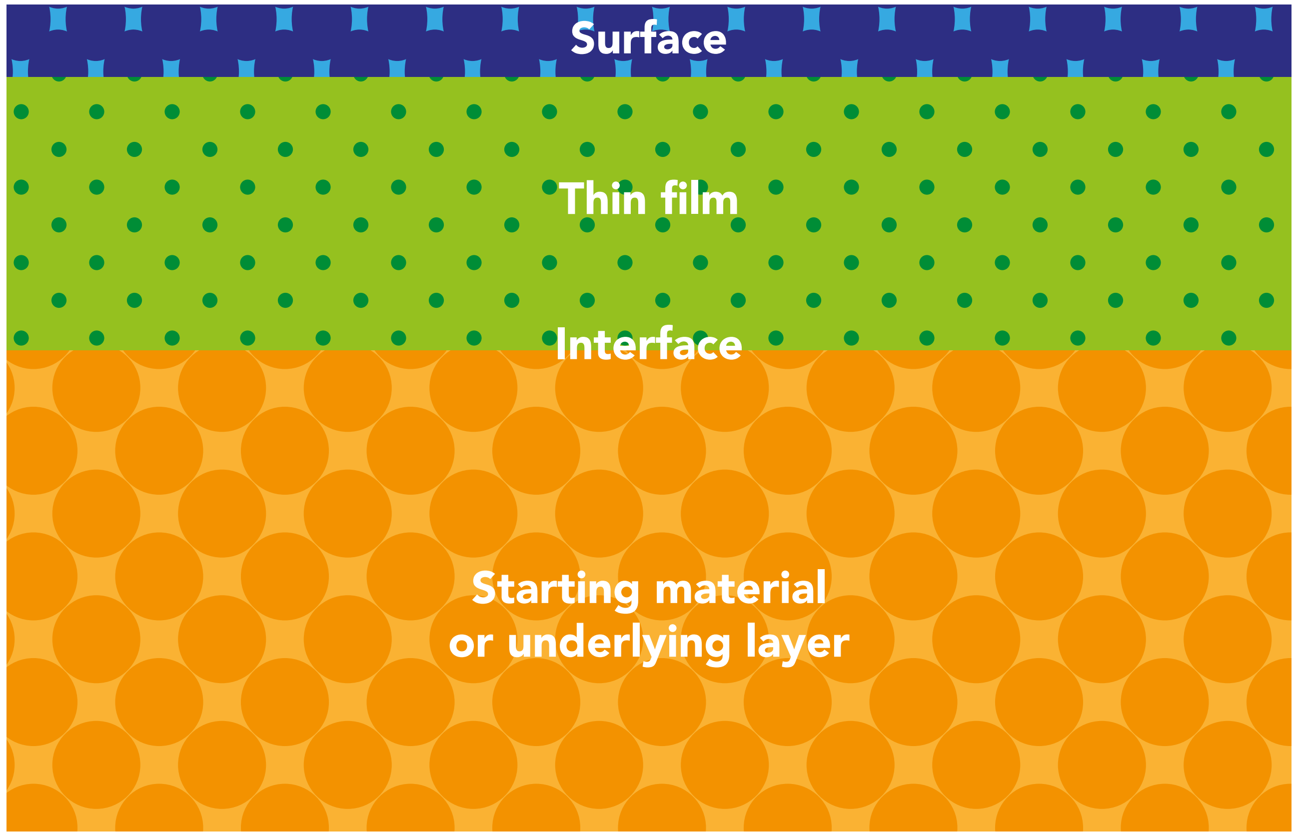
While all of these properties can be affected in different ways, they all link together to cause different magnetic effects in a 'complicated web' according to Dr Holcomb, who tries to shed light on these effects by measuring as much as possible, to compare all factors. For example, she examines the different ways strain, thickness of materials and choice of materials can affect the magnetic properties. She uses a variety of methods including X-ray absorption spectroscopy, which uses synchrotron radiation to excite core electrons, to probe the inner structure of the materials. Dr Holcomb's group combines this kind of technique with others like neutron reflectivity – which uses the reflection of neutrons (at the National Institute of Standards and Technology, NIST) to determine the strength and direction of the magnetism at every layer of the material.

When a material that is normally magnetic becomes too thin, or even at the boundary between two different materials, the magnetic properties can be lost

FERROELECTRIC AND FERROMAGNETIC MATERIALS

In recent years, Dr Holcomb and her team have studied what happens when LSMO, a ferromagnetic material, is placed adjacent to a ferroelectric layer. Ferroelectric materials can become electrically polarised, with one side positively charged and the other negatively, which can switch under an electric field. When placing a thin film of LSMO on this kind of material, Dr Holcomb discovered some curious properties.

At the interface between ferroelectric and ferromagnetic materials, something called magnetoelectric coupling occurs. This means there is a link between the magnetic and electric properties of the material. For example, the magnetic properties of LSMO thin films with a layer of lead zirconate titanate (PZT) on top can be controlled by the presence of an external electric field.



The properties of materials can be very different at their boundaries compared to the bulk of the material. A boundary can be an interface between two materials or the surface where the material meets the air.

Electrical control of magnetism could revolutionise computing (and other devices) by removing the constant need for current in transistors.

By varying the thickness of the LSMO film, Dr Holcomb and her team found that the thicker the layers of LSMO and PZT, the higher the valence (the capacity of the ion to combine with others) of manganese ions within the LSMO. The valence of these ions is linked to the magnetic properties of LSMO, and understanding what affects it can help to create more efficient devices in the future.

> ***Dr Holcomb examines the different ways strain, thickness of materials and the conditions under which materials are grown can affect the magnetic and other properties***

A MATERIALS DATABASE

Although Dr Holcomb has focussed much of her work on LSMO, there are a huge number of materials that exhibit interesting properties on their own and at the interface with other materials. Because of this, keeping on top of the possibilities is a difficult task, especially when the data about each material is not always readily available. Dr Holcomb and her team are in the process of developing a unique kind of database that will give researchers a simple way to compare different materials, using machine learning.

At the moment, the database focuses only on the materials the group's expertise lies with, like LSMO, but they are hopeful they can expand it to include many others. To do this, however, they will need the help of colleagues who will eventually benefit from the database. 'Our database currently includes our own samples, but we'd like to expand it to include others' samples', says Dr Holcomb. 'We are probably going to pull a lot from published literature, but that takes a lot of time and people don't publish all data on a sample. The more help we can get from others, the better.' Dr Holcomb's vision for the database is that anyone using it will be able to plot various properties of a material and see how they change for a variety of samples that meet a given search criterion. Everything from the dependence of magnetism with temperature to the chemical spectrum could be included. 'I've seen something similar done for simple semiconductors, but I've not seen it for complex oxides,' she says.

Behind the Bench

Dr Mikel "Micky" Holcomb

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Research Objectives
Dr Holcomb's work focuses on the properties of the boundaries of two materials. These are often very different to the properties of the bulk of the material and Dr Holcomb aims to develop methods for studying the boundaries specifically.

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- *National Facility Collaborators*
Alpha N'Diaye, ALS; Matthew Marcus, ALS; John Freeland, APS; Alex Grutter, NIST; Brian Kirby, NIST
- *Others*
James LeBeau, NCSU; Norman Tolk, Vanderbilt; Ying-Hao Chu, National Chiao-Tung University; Alejandro Cabrera, Pontificia Universidad Católica de Chile

Bio
Dr Mikel "Micky" Holcomb is an Associate Professor of Physics at West Virginia University. She got her PhD at UC Berkeley (advisor: Ramesh), Bachelors at Vanderbilt (advisor: Tolk) and did an internship at IBM Almaden. While she enjoys collaborating on a variety of topics, her main projects involve magnetic thin films and magnetoelectric heterostructures.

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Q&A

Why are you interested in the interfaces between materials?
Over time, devices have become smaller and smaller. One advantage of this is that we have smaller and faster computers. However, materials on the small scale (whether they be thin films or nanoparticles) do not behave the same as their big counterparts. As we approach these small scales, we will need to understand how these interface effects will change the properties of our devices. Nobel Prize winner Herbert Kroemer said in his acceptance speech in 2000 that "the interface is the device". He might have meant that eventually devices will take advantage of the physics at the interface only when there is no more bulk left.

How thick are these interfaces, is it just one layer of atoms thick or do the layers merge in a more messy way?
It depends on how you make the material; some methods are messier than others. We grow our films with pulsed laser deposition (PLD) with in-situ measurement that allows us to more easily optimise our film quality. We can observe our layers growing one by one, and our interfaces are very sharp. Molecular beam epitaxy is another method to grow high quality films. However, these techniques are not the easiest for industry to scale up, so some researchers specialise in other growth methods which have varying quality. It all depends on what researchers do to verify the quality of their growth process.

Why did you choose to focus on LSMO?
Lots of reasons. First of all, it is one of the few complex oxides that are ferromagnetic at room temperature. While I have studied many different kinds of materials, I really enjoy studying those that have their properties at room temperature. First, they are easier to measure because they do not have to be cooled (though their low temperature properties might also be interesting). But, more importantly, it is more likely they can be used in a real device. I also like LSMO because it has been proposed for a lot of different types of technology. So, even if one does not work out, hopefully another will and we will have already started to understand the important physics. LSMO is also just a good model system. It is in a class of complex oxides called perovskites that have a simple structure, even though their physics can be complex. When scientists try to understand something complex, it can be helpful to start out with something as simple as possible.

How do you decide what parameters you change, e.g. thickness?
For every new material a grower makes, they should optimise their growth process. Ideally, you get a reasonable starting recipe from the literature or a similar material. Then, you have to tweak it. What you tweak depends partly on the growth method. In PLD, the most common variables to adjust are the growth temperature and pressure, but you might also change the laser frequency, fluence, cooling rate or after growth pressure. Sadly, no two chambers seem to be exactly the same, so every recipe has to be optimised if quality is critical. However, all of this tweaking takes a lot of time and money. Everyone has their own standard and this is one of the common things reviewers look out for when reviewing papers.

Where did the idea for the materials database come from?
I was reading an article from WIRED magazine that was talking about using machine learning to aid in cancer research. The general idea was why not let computers take a crack at solving cancer. There is a ton of data in the field and maybe unbiased computers might pick up on something we are missing, particularly since so many variables affect each other. I realised that a similar argument could be made for the materials I study and many others.

Will people have to pay to use your database once it is up and running?
No, but without help it might take us a long time for it to be very useful. We are eager to partner with people that can help make this a good resource. The initial feature will run like a searchable database. You can input what types of materials you want to search, and various parameters (such as thickness and/or growth details). Then you can plot and compare anything you like that meets your search criteria. It will include information on what lab and/or paper the data comes from, so that you can look that up or reference it if you like. How can you help? We need people for a variety of tasks. 1. Just entering data (either from your own work or pulling from published work). I have trained high school students how to do this so even non-scientists could help. If you know how to automate this process, please let me know! This is the biggest hurdle right now. 2. Helping us create a nice website for people to use. I am a physicist, so it might not surprise you that organised programming that is really easy for anyone to understand and use is not my speciality. 3. Aid in implementing machine learning. There is going to be a LOT of data in this database and a lot of it will be graphs. What will be the best things to have the computers compare? I expect there will be a lot of trial and error in the initial analysis.