Annealing Crystalline Thin Films In a Magnetic Field

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Abstract

Magnetic materials are used extensively in the manufacturing of computing device memory. In this project we investigate crystalline thin films composed of layered ferromagnetic (FM) and antiferromagnetic (AFM) materials with the goal of developing next generation computer memory storage. In particular, we have designed a thermal annealer that allows for exposing these magnetic samples to an applied magnetic field while in a vacuum environment. This procedure is important because it establishes an exchange bias in the magnetic thin film material. After the thin films are grown and characterized in the laboratory, they are loaded in the annealer and the pressure is lowered to ~100 mTorr. Next, the samples are heated through the magnetic ordering temperature of the AFM (Neel Temperature), but below the magnetic ordering temperature of the FM (Curie Temperature) so that $T_N<T<T_C$. When $T>T_N$ the magnetic moments of the AFM are in disarray. At this point we apply an external magnetic field, B= .5 T, while allowing the samples to cool down. When $T<T_N$, the interface of the FM-AFM become permanently aligned with the externally applied magnetic field. This anisotropy at the FM-AFM interface is responsible for the phenomena know as exchange bias. Understanding this interface, as well as exchange bias is crucial in developing the materials and devices that will power future generation electronic devices.

Methods

Vacuum strip annealer with associated components

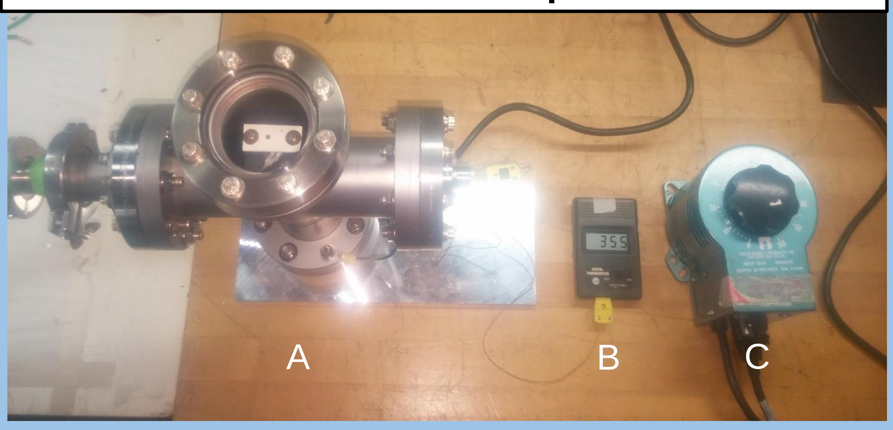


Fig 1

First, we had to construct a vacuum strip annealer that would be used to heat up crystalline thin films in the absence of air. The vacuum annealer system (Fig 1) was fabricated using ultra high vacuum fittings(A). This makes it possible to heat up magnetic thin films in vacuum with a pressure as low as 100 mTorr. The temperature is monitored by the thermocouple and thermometer(B). The temperature is raised and lowered via the variac(C), which is an adjustable ac transformer.

The most challenging portion of the build was the heating element(Fig 2). The element supports a normal operating temperature between 200°C and 600°C.Boron nitride(BN) was chosen because of its chemical and thermal stability. The finished heating element(D) has a titanium tungsten sputter deposition on its underside, used to conduct electricity, which heats the element. We also have an example of the unfinished element(E) with kapton tape applied to mask the circuit pattern for sputter deposition.

Heating element machined from boron nitride with titanium tungsten sputter deposition

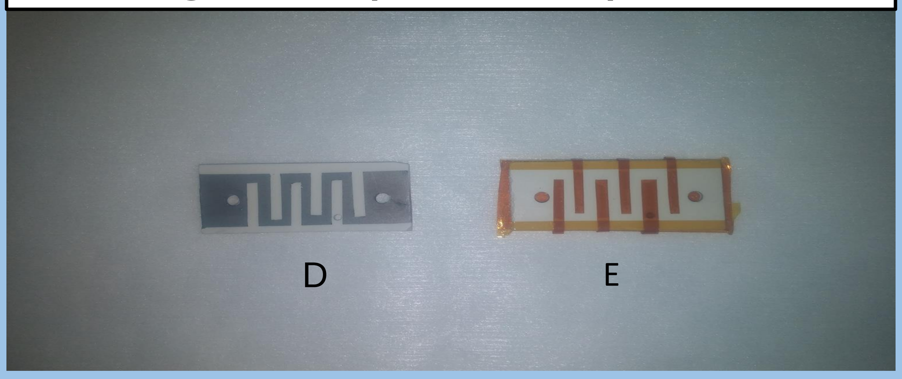


Fig 2

Experimental setup with completed vacuum strip annealer in between magnets

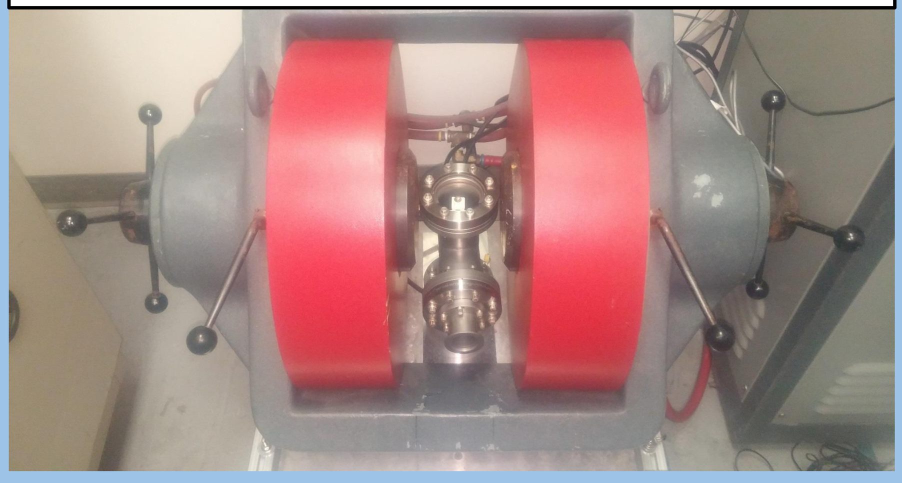


Fig 3

The vacuum strip annealer is seen resting between two powerful magnets (Fig 3). This experimental setup allows us to heat up magnetic thin films in a magnetic field as high as one tesla(T). If a sample is heated past its magnetic transition temperature and cooled slowly in a magnetic field, its magnetic dipole moments can be permanently reoriented.

Ferromagnetism and Antiferromagnetism

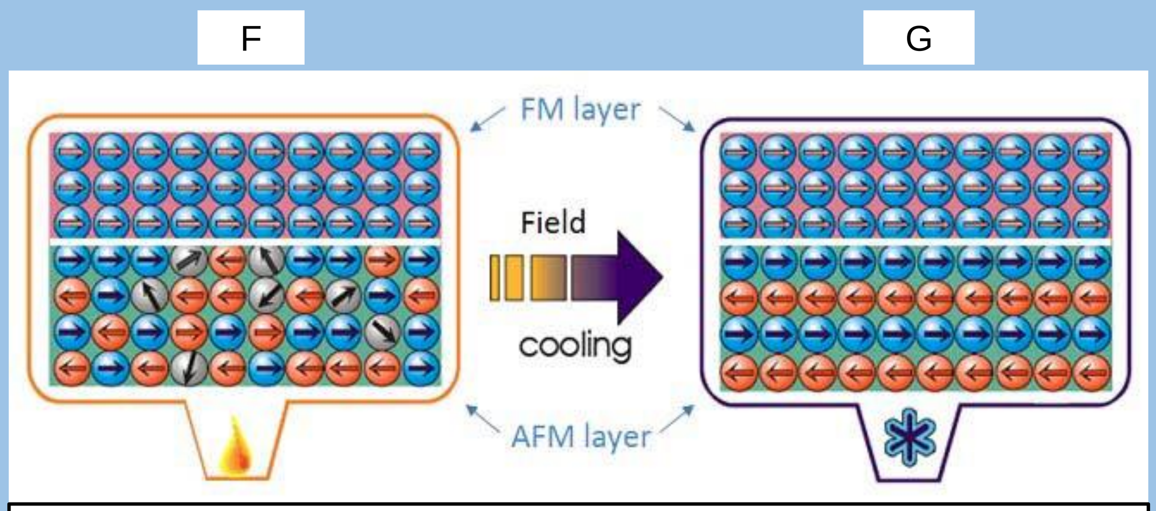
Magnetic Dipole Moment (Below magnetic transition temperature with no externally applied magnetic field)	
Ferromagnetic	↑ ↑ ↑ ↑ ↑ ↑
Antiferromagnetic	↑ ↓ ↑ ↓ ↑ ↓

Fig 4

The magnetic dipole moment may be thought of as a vector quantity which has a magnitude and direction (Fig 4). The direction of the magnetic dipole moment points from the south to the north pole of a magnet. The magnetic field produced by any magnet is proportional to its magnetic moment. Magnetic moments result on the atomic scale due to the movements of electrons. Each electron has magnetic moments that originate from two sources. The first is the orbital motion of the electron around the nucleus. The second source of electronic magnetic moment is due to a quantum mechanical property called the spin of an electron. If the magnetic dipole moments of a material point in the same direction, the material will have a net magnetization, and is called **ferromagnetic**. There are very few elements that are ferromagnetic. The three most common are iron, cobalt and nickel. If an object has magnetic dipole moments that are equal and opposite in direction (any direction-think 3 dimensional), then the object has zero net magnetization, and is called **antiferromagnetic**.

Procedures

The lab grows crystalline films that can be several monolayers in thickness. Of particular interest is the affect that annealing in a magnetic field has on ferromagnetic (FM) and antiferromagnetic (AFM) thin films[Fig 5]. The thin films are heated past the AFM magnetic transition temperature in the vacuum annealer at a pressure of ~100 mTorr. When the sample exceeds this (Neel) temperature of the AFM, the magnetic dipole moments of the AFM become disordered (F). An external magnetic field is then applied so that the **interface** of the FM-AFM has magnetic moments that are parallel with each other. The rest of the AFM bulk structure follows suit as to achieve zero net magnetization. The thin film is then cooled in the presence of the magnetic field. When the film is cooled the magnetic moment of the AFM has now been permanently reoriented(G), even when the external magnetic field is removed.



After magnetic thermal annealing, an AFM becomes much more ordered and pins(i.e., fixes) the adjacent FM layer.

Fig 5

Results

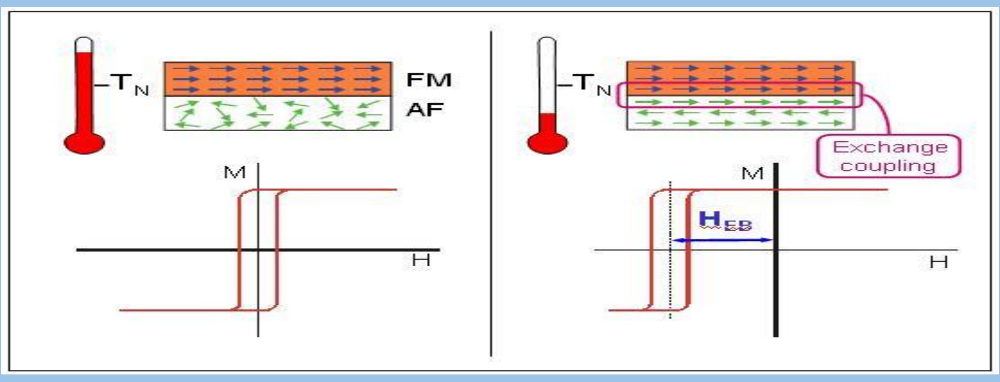


Fig 6

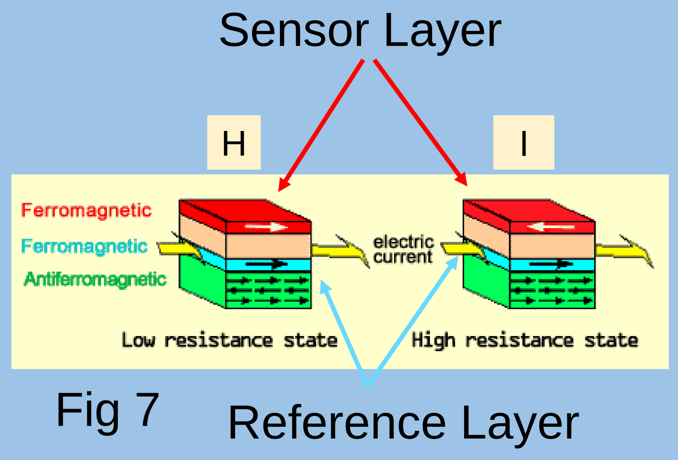


Fig 7

Thin film grown in lab

Fig 8

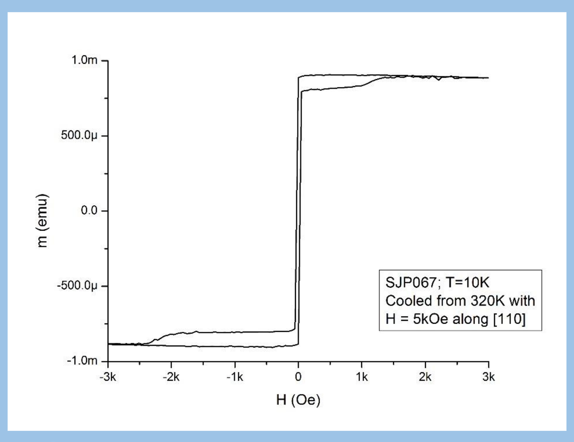


Fig 9

It has been observed that heating up these magnetic thin films beyond their respective magnetic transition temperatures and cooling them in the presence of an external magnetic field allows us to alter the magnetic moments permanently. When the interface of the FM-AFM thin film form an exchange coupling (Fig 6), the effect is an effective pinning of the FM magnetization parallel to the topmost layer of the AFM, giving rise to the exchange bias phenomenon. Some of the key magnetic devices found in advanced electronics like computers utilize exchange bias to pin (i.e. fix) the magnetization of a FM reference layer in a fixed direction in space. Relative to the fixed direction of magnetization in the reference layer, one may then align the magnetization direction of a second ferromagnetic layer, called the sensor layer at an arbitrary angle (Fig 7). According to research done at Stanford University, if the direction of magnetization in the sensor layer is rotated by a magnetic field, the device acts as a sensor for the direction and strength of the magnetic field. If magnetization in the sensor layer is used to define two distinct states, either parallel (H) or antiparallel (I) to the reference layer, we have a memory cell consisting of “1” and “0” bits. The key requirement is to keep the reference layer unaffected by whatever one does with the sensor layer – and this is assured by exchange bias. In general, the effect is defined as the unidirectional pinning of a ferromagnetic layer by an adjacent AFM.