

**VERTICALLY ALIGNED NANOCOMPOSITES IN MAGNETIC THIN
FILMS**

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

	Page
TABLE OF CONTENTS.....	1
ABSTRACT.....	2
CHAPTER	
I. INTRODUCTION.....	3
II. METHODS.....	9
Target preparation.....	9
Pulsed laser deposition.....	12
Transmission electron microscopy (TEM).....	14
III. RESULTS.....	16
IV. CONCLUSION.....	24
REFERENCES.....	26

ABSTRACT

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With the advent of ferromagnetic materials for magnetic memory among other applications, increased attention has been given to understanding the properties of these ferromagnets. Here, a vertically aligned nanocomposite (VAN) system is examined for ferromagnetism and the tuning of its magnetic properties. Specifically, different compositions of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$, grown by pulsed laser deposition (PLD) are tested for varying properties. Growth of different compositions of the VANs allows for an understanding of how exactly the system is different than conventional ferromagnetic materials. This new system, utilizing a combination of two phases as opposed to the thoroughly explored single phase scheme, yields interesting results that can open the door for more ferromagnet applications.

CHAPTER I

INTRODUCTION

Due to their wide varying properties, ferromagnetic materials have experienced a surge in research focus recently despite the fact that their properties have been understood for some time. Specifically, ferromagnetic thin films have seen wide applications in the non-volatile memory field among many others. However, this thesis will provide more focus on the interface properties of ferromagnetic thin films. That is, attention will be given to the impact of different surface interfaces such as those found in multilayer films. By understanding the interface material properties of these films, a greater understanding will be gained about the material physics and its potential applications.

Single phase ferromagnetic thin films have been well-studied in the past, but vertically aligned nanocomposites (VANs), a two-phase configuration, is not yet fully understood^[1]. Using another phase can significantly alter the properties of a given material and can introduce a host of new applications as well as growth mechanisms. This accounts for the recent attraction of self-assembled VANs with two immiscible oxides grown heteroepitaxially on single crystal substrates^[2]. As the name suggests, VANs are vertically oriented interfaces as opposed to the more common horizontal interfaces used when growing multilayer thin films. Nanocomposite films with a vertical architecture have a larger interfacial area and intrinsic heteroepitaxy in three dimensions^[3].

More interesting properties arise when one observes the effects of ferromagnet-insulator-ferromagnetic structures evident in many VAN systems. This arrangement, also known as a

magnetic tunnel junction (MTJ), enables spin polarized tunneling from ferromagnet to ferromagnet, through the insulator layer. Theoretically, this phenomenon can be understood from a quantum mechanical perspective. The relative potential of the ferromagnets can be considered as 0 eV while the insulator behaves as a barrier with some certain energy. Furthermore, components of a ferromagnet, called magnetic dipoles, align within given domains and create an overall magnetization. The relationship between the magnetizations of the ferromagnetic layers further drives spin-assisted tunneling. Thus by controlling the insulator layer, that is the surface morphology of the VAN structure, one can tune the magnetic properties of the multilayer film.

Another application, one previously explored in this group and a source of motivation for this project, is the use of a ferromagnetic dopant with YBCO superconductors to improve their properties. In fact, comparison data will be shown later in the results section that shows how the critical current density of our materials system compares to a reference YBCO superconductor and the improvement in the superconductor by using different growth ratios of the VAN system. Magnetic nanoinclusions in the VAN system form could possibly increase the critical current density without a poisoning effect on the other properties of the superconductor^[4].

Superconductors have the very unique ability of carrying electrical current with very near to zero resistance. This renders them especially useful in practically any application requiring or desiring lower power consumption. Such a versatile use has caused a great deal of research on different superconducting materials and improvements to their qualities such as critical current density and critical temperature. The critical current density and critical temperature are the maximum current density and temperature that, respectively, beyond which the superconductor will stop

behaving as a superconductor. Thus, improvements to these properties are desirable as many future power applications of the superconductors require larger critical current densities, especially at higher fields and temperatures higher than absolute zero^[5-8]. Materials science has devoted the research of several different methods to try and improve superconductors for future use.

The current class of superconductors being researched are known as high temperature superconductors since they exhibit typical superconducting properties at temperatures much higher than absolute zero. A brief introduction to superconductors, particularly flux pinning, is given here so that an understanding of the goal of this research project can be understood. Special attention is given in this introduction to flux pinning and the pinning force.

Flux pinning, which is described as the existence of magnetic fields in the interior of type II superconductors in the form of vortices (one unit of flux quanta), is an integral property which allows for engineering of defects to increase the possible critical current density. Applying an electric current initiates an interaction with the applied magnetic field that results in a lateral force, the Lorentz force, which acts on vortices causing them to move and dissipate energy. This energy loss appears as electrical resistance in the superconductor. The greater the applied current density, the greater the Lorentz force. Energy reducing crystalline defects in the superconducting material form a force called the pinning force, which counteracts the Lorentz force. The magnitude of this pinning force dictates the amount of superconducting current density that a particular superconductor can support, as the Lorentz force is proportional to both the applied magnetic field and the current density^[9].

The inherent cause of the pinning force, material defects, makes it possible to engineer new defects and materials to augment the flux pinning in a given superconductor. With improved flux pinning, one can create a superconductor that can support larger critical currents. Particularly useful materials for improving flux pinning are thin films, grown through several different methods, which have a large amount of inherent defects^[7, 10]. YBCO superconductors already have, by nature of their production (chemical vapor deposition, sintering, molecular beam epitaxy, pulsed laser deposition etc.), many inherent defects which make them ideal candidates for improvement of flux pinning by introducing additional defects. Since flux pinning most directly impacts the critical current density that a superconducting material can support, including defects that affect flux pinning will work to increase the critical current density.

The prior work in our group utilized defects in the form of the $(\text{Fe}_2\text{O}_3)_{0.5}:(\text{CeO}_2)_{0.5}$ system which actually consists of a ferromagnet (Fe_2O_3) and an insulating material CeO_2 . The Fe_2O_3 had previously proved successful in improving the flux pinning mechanism in the YBCO thus enhancing the current density properties of the superconductor. CeO_2 is chosen as the insulating phase based on its good lattice matching with YBCO films after an in-plane 45 degree rotation and good chemical compatibility with YBCO. Furthermore, the CeO_2 layers can attribute to more high density interfacial defects on their interface with the YBCO film which may also attribute to enhanced flux pinning^[4]. Below are featured some graphs which point to the usefulness of the inclusion of the VNA films with YBCO superconductors. A clear correlation exists between different phase ratios and an improvement in the critical current density.

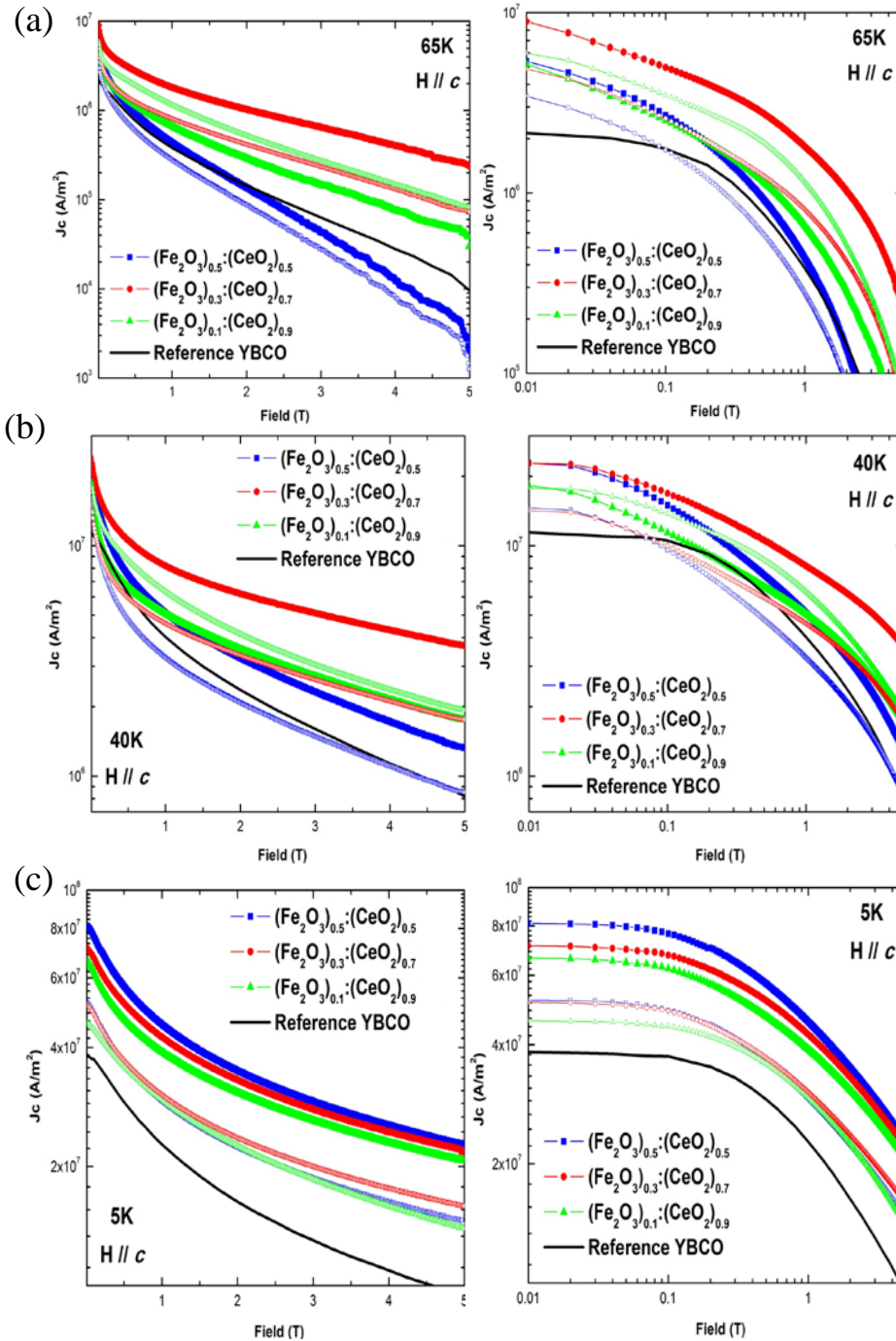


Figure 1: Critical Current Density of $(\text{Fe}_2\text{O}_3)_x:(\text{CeO}_2)_{1-x}$ at Temp: (a) 65K, (b) 40K, (c) 5K

The graphs in figure 1 above show the critical current density of the $(\text{Fe}_2\text{O}_3)_x:(\text{CeO}_2)_{1-x}$ VAN system as opposed to a reference un-doped YBCO semiconductor film. By observing the graphs one can clearly see that, regardless of the temperature, there is a noted enhancement in the critical current density with inclusion of the VAN system. This inclusion, albeit using a different

system than the one focused on in this project, provided a basis for continued exploration with a different VAN system. Thus, we attempted the use of a different VAN system to see its impact on the critical current density in superconducting YBCO.

The $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ is one such vertically aligned nanocomposite system. The $(\text{CoFe}_2\text{O}_4)_x$ behaves as a ferromagnetic material in this system while the $(\text{CeO}_2)_{1-x}$ is the insulating material.

The x represents the weight percentage of each material. Increasing or decreasing this weight has a profound impact on the nanostructural morphology and magnetic properties of the material.

The different relative weights are fabricated by preparing a target for each composition, a process that will be explained in the methodology section of this thesis. The properties of these thin film multilayer structures are then characterized using transmission electron microscopy and vibrating sample magnetometry, to acquire data on both nanostructure and magnetic properties.

CHAPTER II

METHODS

The preparation and testing of thin films, magnetic or not, is a process that involves several steps consisting of: initial powder preparation, proper mixing, target sintering, additional preparation steps, and finally film deposition from the synthesized target. The deposited film is then tested through several methods to discuss its different properties. This section will discuss these steps concerning thin film preparation and will provide an understanding of how to begin from chemical powders and result in a testable thin film.

Target preparation

In preparing the powders for initial steps, one must decide on the powders necessary to create the particular compound desired in the film. Materials used in the film are usually not available in powder (although CeO₂ used in this experiment is) and must be created by mixing other powders and can often be easily characterized by a chemical equation. Here, the method for synthesizing the CoFe₂O₄ necessary for the target used will be presented in a thorough manner to highlight the necessary steps for mixing powders to obtain a desired target. CoFe₂O₄ requires the powders Co₂O₃ and Fe₂O₃ mixed in certain proportions depending on the desired mass of CoFe₂O₄ powder.

As mentioned above, the calculations performed for CoFe₂O₄ can be understood through the following chemical reaction:



The calculation here will be carried out for a desired weight of 10 grams of CoFe_2O_4 but a note will be indicated next to this weight. This calculation method can be used simply to compute the amount of powder needed for any variation in weight of CoFe_2O_4 powder. First the following information is needed:

Molecular Weight(CoFe_2O_4) = 234.620795 grams/mol

Molecular Weight(Co_2O_3) = 165.86459 grams/mol

Molecular Weight (Fe_2O_3) = 159.6882 grams/mol

According to the equation, one can determine the amounts based on the coefficients of each compounds in the equation as follows:

For Co_2O_3 :

$$10 \text{ grams CoFe}_2\text{O}_4 \times \frac{1 \text{ mol CoFe}_2\text{O}_4}{235 \text{ grams CoFe}_2\text{O}_4} \times \frac{1 \text{ mol Co}_2\text{O}_3}{2 \text{ mol CoFe}_2\text{O}_4} \times \frac{166 \text{ grams Co}_2\text{O}_3}{1 \text{ mol Co}_2\text{O}_3} \quad (\text{Eq.2})$$

For Fe_2O_3 :

$$10 \text{ grams CoFe}_2\text{O}_4 \times \frac{1 \text{ mol CoFe}_2\text{O}_4}{235 \text{ grams CoFe}_2\text{O}_4} \times \frac{2 \text{ mol Fe}_2\text{O}_3}{2 \text{ mol CoFe}_2\text{O}_4} \times \frac{160 \text{ grams Fe}_2\text{O}_3}{1 \text{ mol Fe}_2\text{O}_3} \quad (\text{Eq.3})$$

These calculations yield a weight of 3.534 grams Co_2O_3 and 6.806 grams of Fe_2O_3 powder.

Including rounding errors, this approximately equals ten grams, the original weight desired for the actual target.

Once the proper amount of the aforementioned powders is weighed out, one can continue onto the next step of the process: mixing the powder. Take note that since CeO_2 powder is available, the process for preparing that portion of the target begins at this stage. Furthermore, note that the

amount of CoFe_2O_4 obtained and the amount of CeO_2 powder used should maintain the desired ratio of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$. That is, the x and $1-x$ proportions should be kept constant.

The mixing process can be done in one of two ways: using a mechanized mixer or by mortar and pestle. The mortar and pestle process was used in this work and will thus be the method explained here. The CoFe_2O_4 must first be obtained before mixing in the CeO_2 so the process begins with placing the measured powders of Co_2O_3 and Fe_2O_3 in the mortar. Then an alcohol, such as butanol, is used to mix the powders in solution. This part of the process can also be done in two different ways: the user can continue mixing the powders until all the butanol evaporates or a hot plate can be used if fast evaporation of butanol is desired (that is, if time is an issue). This may be repeated several times to ensure a good resultant powder is obtained. Finally, the CeO_2 powder can be mixed in once a desirable CoFe_2O_4 powder has been obtained. Mixing of this final solution will yield the powder for the target.

Once the two powders are mixed, the powder is then ready for sintering, that is to be pressed into a solid target and then heated. In this work, the powders were placed inside of a holder and then pressed using a mechanical press to turn the powders into a solid target. One should examine the pressed target to ensure that the powders were indeed mixed well. The target preparation, albeit tedious and including several steps, is a crucial part of the thin film preparation process. Without a good, clean and well mixed target, the thin film quality will greatly decrease. Thus, at each step, materials should be evaluated to ensure that the final quality of the film will be good. After the solid target is deemed good, it is placed in a tubular heater for several hours at a high temperature for final solidification.

Pulsed laser deposition

Pulsed laser deposition (PLD), a physical deposition method, is the chosen method for growing thin films in this work. In this section, a brief overview of the pulsed laser deposition mechanism will be described and then further specified for this work. The target used for PLD is the one for which the synthesis method was described previously. Several parameters must be decided and confirmed for PLD to result in smooth thin film growth.

Especially for heteroepitaxial growth, that is the growth of films on substrates of differing material, considering several parameters such as crystal structure and lattice parameters are crucial factors in film growth. Films grown on substrates with mismatching of these parameters may result in amorphous growth, island shaped growth, or the existence of many defects. Thus, to successfully grow smooth films using PLD, one should ensure that the film and substrate material are compatible. Note that it is not necessary that the crystal structure or lattice parameter be exactly the same, but they must at least be of compatible types.

PLD is a somewhat non-equilibrium deposition method, unlike other methods such as electron beam evaporation or thermal evaporation. A chamber containing a target holder, sample (substrate holder), gas flow valves, and vacuum valves is used in this process. PLD is done at relatively high vacuum, utilizing both mechanical and turbo pumps for vacuum generation. Once the chamber is vacuumed to the proper level and the sample substrate is heated to the desired temperature, the PLD process can begin. The vacuum is important for removing any impurities that might be in the chamber before depositing a sample. A laser is fired upon (focused using beam optics) the target developed in the previous part of this work. The laser (photons) incident

on the target material imparts kinetic energy to target atoms and provides more available energy for diffusion on the substrate/depositing surface. As the surface of the target is heated, the PLD is constantly rotating so that the laser energy is imparted over the entire surface of the target. A plume is developed containing atoms of the target and leaves the target surface. The substrate is held across from the target so as to be available to the incidence of the plume of target material. The substrate is also heated (the substrate holder itself is heated to a high temperature) to further facilitate good diffusion. A classic PLD chamber (interior view) can be seen below in the figure.

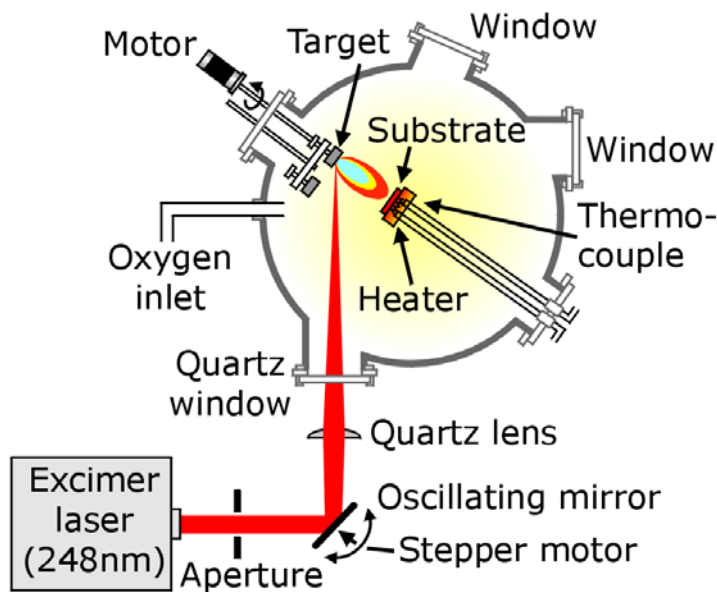


Figure 2: Classical Interior View of a Pulsed Laser Deposition Chamber (courtesy of MSU ECE website)

The growth rate and quality of the deposited film are dependent quantities. That is, it is possible to deposit film at higher speeds (thus less time) with reduced quality. Depending on the needs of the user, the deposition rate or number of pulses can be increased for faster deposition with lower quality.

In this work, the target loaded was the previously discussed $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ target. A film was grown for $x = 0.1, 0.3,$ and 0.5 . The substrate (which was also heated to 500 degrees Celsius) was Strontium Titanate (SrTiO_3).

Transmission electron microscopy (TEM)

One of the important information derived from a thin film is the micro/nano structure in the film. Especially for vertically aligned nanocomposites (VANs) the material systems studied in this work, this micro/nano structure is very important for understanding the vertical alignment of the secondary phase and further linking this alignment with behavior of the material under conditions such as varying magnetic fields.

The sample size required for transmission electron microscopy is actually very small, since the TEM process detects the transmission of electrons through a material. The thicker the material is, the more difficult it is to transmit electrons. Thus, a very important process is the sample preparation. That is, taking the sample from its original size and obtaining a small and extremely thin sample for use in a transmission electron microscope. The preparation process will be described in this section.

The sample size of the substrate and thus, that of the deposited thin film is usually quite large. In order to reduce the size enough for TEM exploration, a small piece of this substrate and thin film, only a few millimeters in length and width should be cut. This can be done in a number of ways but in this work, it was done using a diamond pen. Once a small sized sample is obtained, the substrate under the film must be polished away. This is because one does not desire that the

substrate should interfere with the measurement of the thin film itself. Note here that the thin film deposited on the surface is typically on the low hundreds of nanometers thick while the substrate is orders of ten larger. Thus a polishing machine was used in this work to reduce the substrate and film thickness to approximately 100 microns or thereabouts (sometimes it can be reduced down to 60 microns).

After completion from the polishing machine, the thin film thickness (60 microns) is still too thick to use in a TEM. Further reduction of the thickness is possible by using a grinder. This allows the user to reduce the size to downwards of 30 microns. The user must then polish the surface such that it is quite smooth (this can be checked with an ordinary microscope) and then place it for ion milling. This creates a small hole around which to test in the TEM. Once the ion milling is complete, the sample is ready to take for TEM measurement.

The TEM process, as suggested by the name, involves the transmission of electrons through a surface for imaging. The electrons are generated by what is known as an electron gun and the resulting beam is focused onto the sample through electron beam optics. Since there are different features on the surface, particularly the different phases and their densities, the electrons are able to transmit more or less easily in different portions of the film. These electrons are in turn incident on a detector which determines the intensity of each electron. By mapping these intensities, the characteristics of the sample can be obtained. Further details on the results of the TEM, as well as images and analysis, will be included in the results portion of this thesis.

CHAPTER III

RESULTS

Thin films were deposited using PLD on the targets developed using the calculation methods developed in the previous section. Specifically films were grown for the $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with x values of .1, .3 and .5. These constitute different overall compositions so that one can compare the difference between having a proportional amount of CoFe_2O_4 and CeO_2 and having a higher ratio of CeO_2 phase.

The films fabricated were fabricated with thicknesses between 150-200 nm. Then, procedures were performed as mentioned above to obtain samples for TEM, STEM, and VSM measurements.

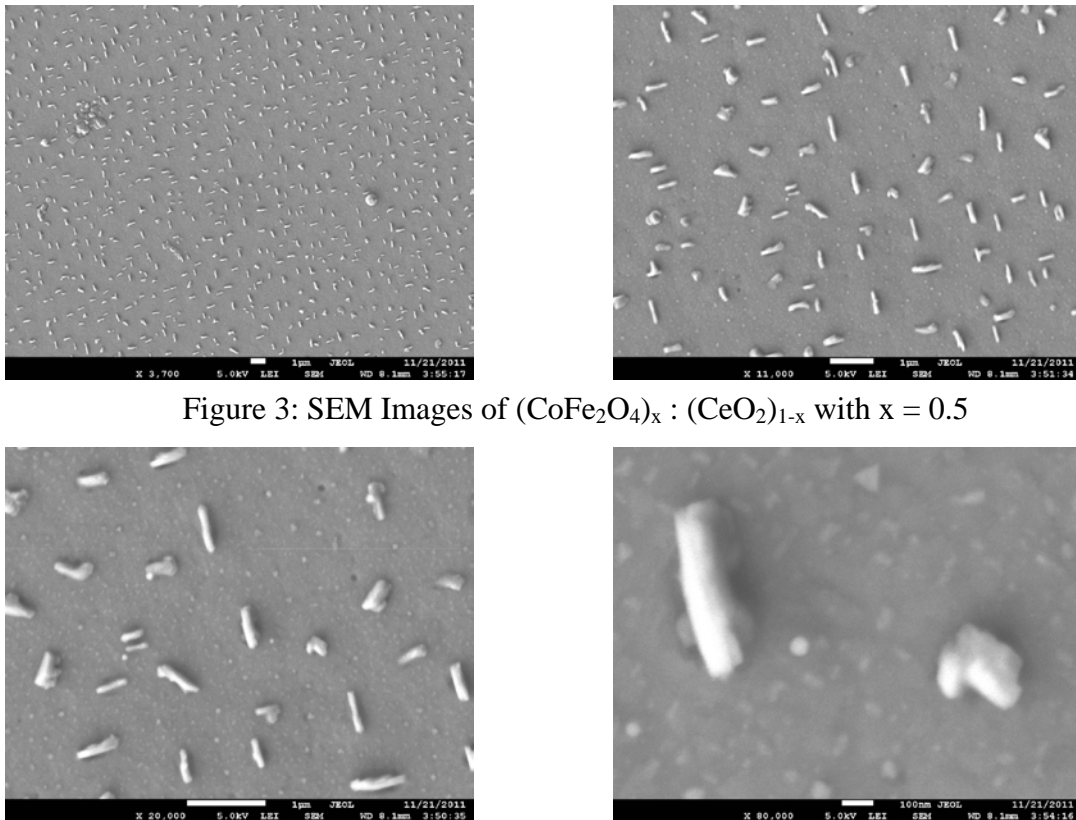


Figure 3: SEM Images of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with $x = 0.5$

Figure 2 above features images taken by placing samples of the $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ film, with $x = 0.5$, in a scanning electron microscopy (SEM). By observing the two phases in the images, one can see the ratio in which the two phases are grown. Just by visual observation, the two materials display an almost half-to-half ratio.

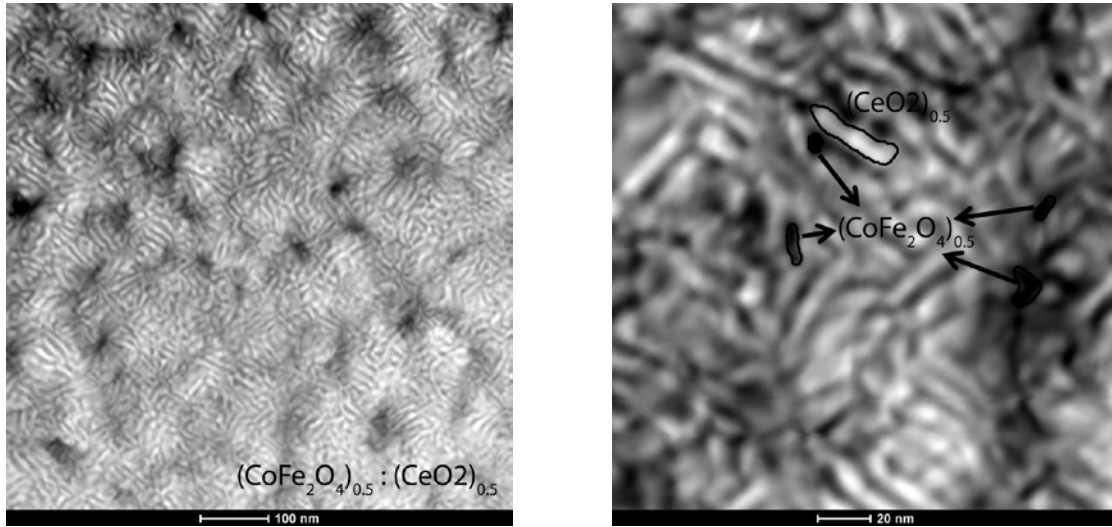


Figure 4 (a): STEM and Close-Up STEM images of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with $x = 0.5$

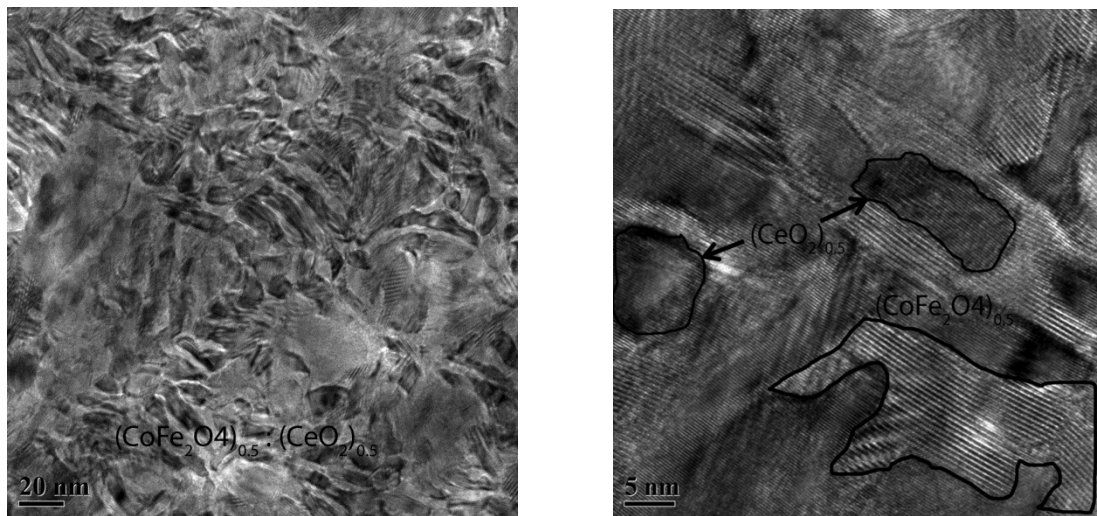


Figure 4 (b): TEM and Close-Up TEM images of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with $x = 0.5$

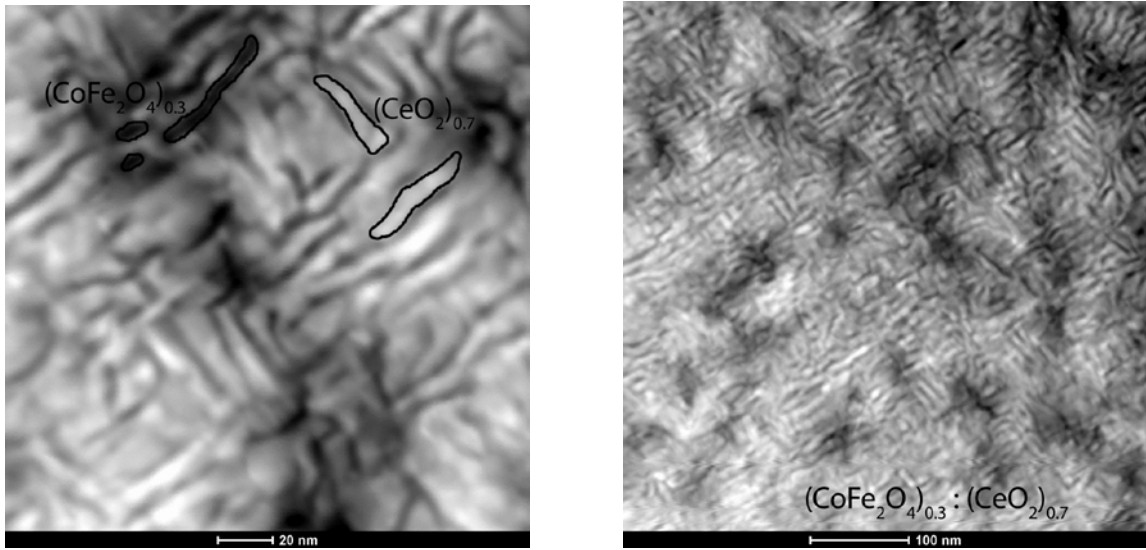


Figure 5 (a): STEM and Close-Up STEM images of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with $x = 0.3$

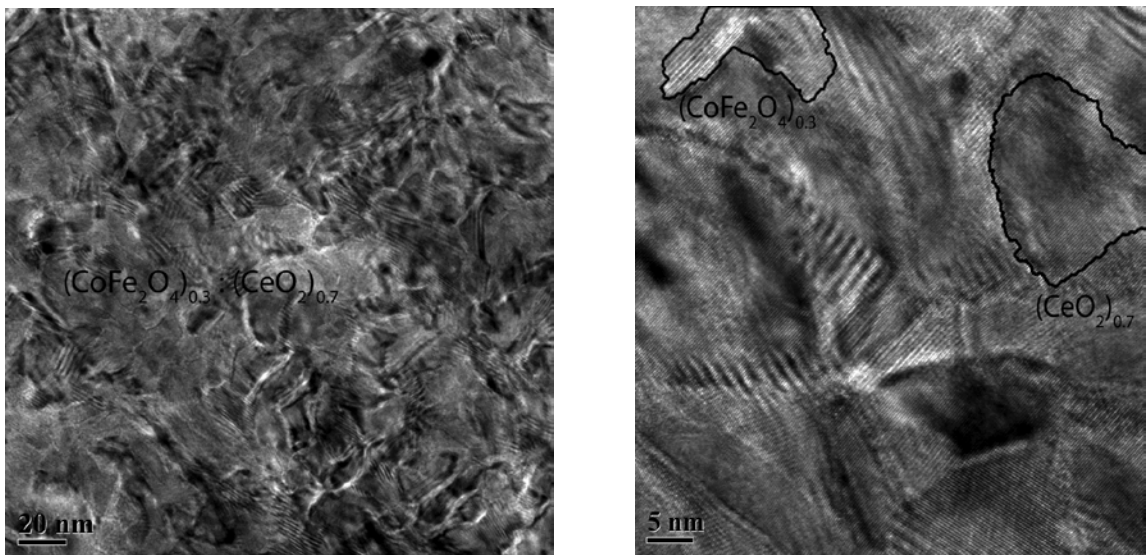


Figure 5 (b): TEM and Close-Up TEM images of $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$ with $x = 0.3$

The above TEM and STEM images give some understanding of the microstructure of the two phases. Even a cursory glance allows one to see how they align with each other and that there is indeed a vertical alignment. The labels in the figures are intended to provide the reader with some understanding of which material in the matrix is which. Through observation, one can see that the microstructural morphology of the VAN system changes with different growth ratios.

With data on the current density improvement/tuning of the YBCO superconductor with a magnetic thin film inclusion, included below, the reader can see how different ratios impact the tuning. In fact, with the knowledge of what type of thin film structure was used in the growth of the superconductor, one can better understand the mechanism driving the improvement of the superconductor.

The critical current density curves vs. applied field plotted are for the superconducting YBCO with the VAN system in one of two inclusion types: cap layer and buffer layer. As the names suggest, a cap layer is the growth of the vertically aligned nanocomposite on-top (as a “cap”) of the superconductor such that the structure is substrate-superconductor-VAN layer. The buffer layer is the growth of the VAN layer in-between the substrate and superconducting YBCO layer such that the structure is substrate-VAN layer-superconductor. These two different methods of including the ferromagnetic VAN provide for different changes to the pinning landscape of the YBCO which in turn affect the improvement of the critical current density.

Fundamentally, the inclusion of a defect helps improve the current density because, as mentioned in the introduction, the defect provides a pinning force which counteracts the Lorentz force caused by the applied current density. This in turn results in less power dissipation which is the goal of the use of superconductors in electronics^[11]. However, by including the ferromagnetic VAN, one must also examine the interaction between the magnetic properties of the material and the superconductor itself. Recently, this has been the focus of many research groups^[12-14]. A key factor to note here is the Lorentz force on the vortex lattice and the pinning force that might arise as a result of the interaction of any defects (acting as pinning centers) with the vortex lattice.

These forces are actually in opposition of each other opening the door to some methods of tuning. Columnar magnetic defects in the superconducting material have been found to have larger magnetic pinning energy than the pinning energy associated with other types of defects^[15]. These concepts can be used to interpret the results obtained below in Figure 6.

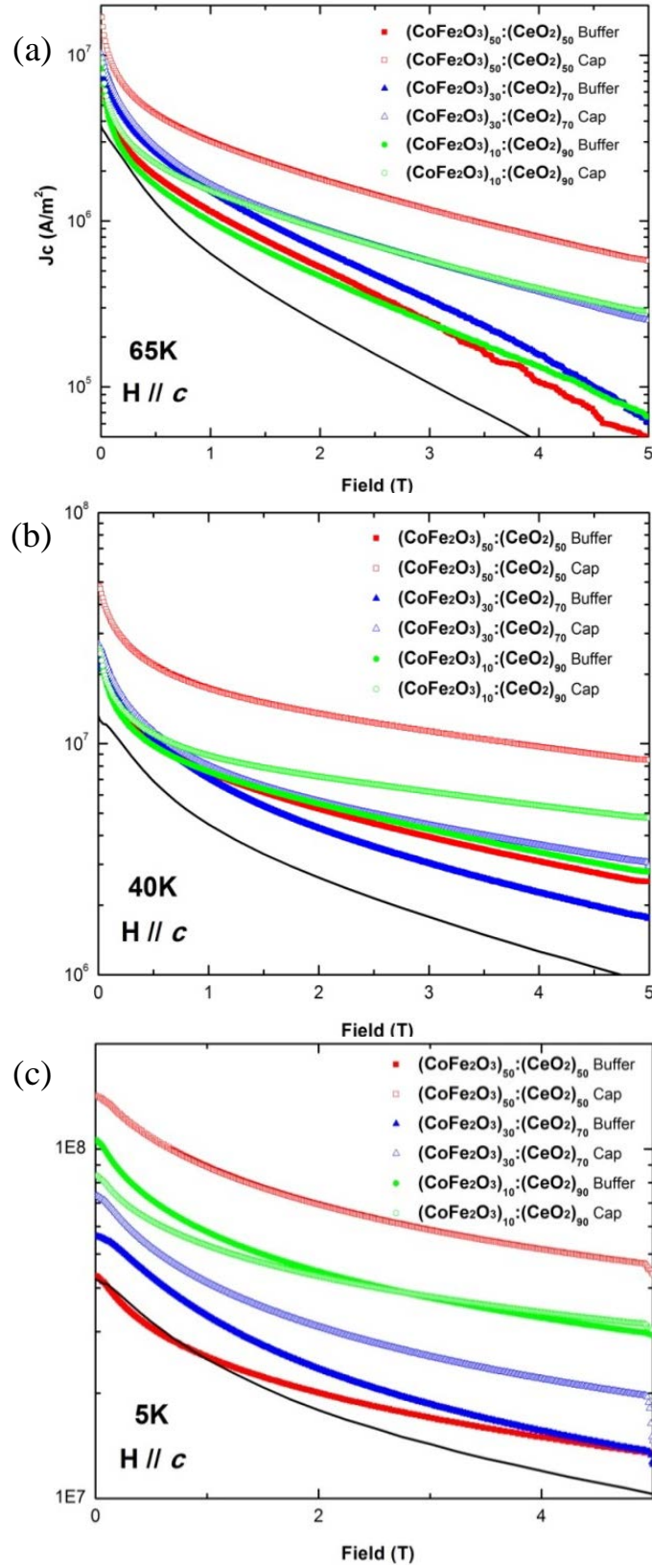


Figure 6: Critical Current Density of $(\text{CoFe}_2\text{O}_4)_x:(\text{CeO}_2)_{1-x}$ at Temp: (a) 65K, (b) 40K, (c) 5K

Figure 6, plots of the critical current density of a YBCO superconductor with a magnetic thin film inclusion, shows how different ratios (either as cap or buffer layers) affect this density. As the current density is one of the most important factors in determining how “good” the superconductor will be in application, any experiment must provide evidence of improvement to this property. The plots in figure 6 clearly exhibit experimental proof that this improvement is indeed the case in this project.

With these graphs, one can interpret the results in terms of flux pinning and the interaction between the ferromagnetic VAN and the superconductor. The first property to note from the graphs in figure 6 is that in general, the cap layers exhibit higher maximum critical current density and thus, have a higher density at higher field values. Conversely, the buffer layers have a lower maximum value of critical current density than do the cap layers. Samples with a smaller ratio of the magnetic phase (CoFe_2O_4) have, in general, a smaller critical current density. This is likely caused by the decreased interaction between the ferromagnetic material and the vortex lattice of the superconductor. That is, there are less magnetic pinning centers as compared to the films fabricated with more of the magnetic phase. Of course, as seen in the graphs, there are some slight exceptions to this rule and this will be discussed in the paragraph on the temperature effects on the superconductor.

The buffer layers also prove somewhat less effective than the cap layers. This may be because the buffer layers cause a general degradation of the properties of the YBCO superconductor and possibly change the way the intrinsic defects of the YBCO, those that make it so desirable as a superconductor, effect the pinning landscape ^[4]. Magnetic inclusions have, according to figure

6, proven effective overall in increasing the critical current density, evidenced by the plots showing that all the different types of inclusions featured a greater critical current density than the undoped-YBCO superconductor (black line). Existence of magnetic pinning centers in addition to pinning centers from the intrinsic defects of the film is thus substantially proven.

Temperature variance has the expected effect on the superconductors; as the temperature decreases, the superconducting properties of the YBCO increase. However, there is some effect from the temperature on the magnitude of pinning from the magnetic inclusions. At the higher temperatures, some of the films with less magnetic phase actually feature a larger critical current density than their counterparts with more magnetic phase. As the temperature becomes lower however, the films with larger magnetic phase ratios exhibit the largest critical current density. One can thus conclude that magnetic pinning is stronger than the pinning due to intrinsic defects at low temperatures.

CHAPTER IV

CONCLUSION

The objectives of this project were to attempt the growth and analysis of materials, specifically $(\text{CoFe}_2\text{O}_4)_x : (\text{CeO}_2)_{1-x}$, in the vertically aligned nanocomposite system. Grown through PLD, such films with different growth ratios (made by changing the value of x) were indeed grown and observed as part of this project. Data is provided in the previous results section in the form of microscope images (for TEM and STEM) and graphs of the critical current density of the magnetic inclusion in the YBCO superconductor.

Observation of the acquired images revealed the changes in microstructure as the growth ratios were varied. From these images, one can conclude that more CoFe_2O_4 , the magnetic material in this particular VAN system, results in a denser and larger domain of CoFe_2O_4 . These different growth ratios produce surface morphology differences which, with the help of the TEM and STEM images and the graphs of critical current density, can be used to narrow down exactly how the growth ratio change affects the magnetization dynamics of the magnetic CoFe_2O_4 . This understanding can be further applied to use in the aforementioned applications including superconductors and magnetic tunnel junctions among many others.

Finally the graphs of critical current density of the YBCO with the magnetic inclusion provide the final piece of information necessary for seeking a deeper understanding of the application to superconductors. Each graph has a reference YBCO measurement (the lowest black line) to compare to the different magnetic inclusions. In all three temperature settings, the sample producing the best performance is a YBCO with a magnetic inclusion of a cap layer of the VAN

film grown with a half-to-half ratio. Thus, varying the growth ratio was not particularly helpful in improving this aspect of the superconductor. However, one can certainly note the property typically associated with superconductors and that which is a prevalent issue for the viability of superconductors. A marked increase is noted when decreasing the temperature and this is because normally, superconductors exhibit the “best” behavior as the temperature approaches absolute zero. The goal from here on will be to improve YBCO films, with magnetic inclusions, to allow for high critical current density at room temperature.

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