# Electron Microscopy Images Reveal Magnetic Properties

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**Abstract**

Nanoalloys are a fairly new and highly appealing topic of study. Research has shown that different properties and characteristics may be found by adjusting the size and compositional differences during manufacturing. These alloy mixtures may yield unique, consistent nanoalloys that meet or exceed the desired effects, or show properties in common with different nanoalloys with similar crystal structures. Electric, thermodynamic, and magnetic applications are just some of the different areas that can be changed due to fine tuning a nanoalloy's size and composition.

Nanomagnets are one of the next big investments in the electronic world. Current applications include high-energy-product permanent magnets, hard disk storage technology, and innovations in the field of medicine. It is well known that transistors have rapidly shrunk in size over the past few decades. However, shrinking the size of usable magnets has been difficult. Currently, there is a large field of research that seeks to find affordable, powerful, and effective nanosized magnets.

A procedure for characterization of nanomaterials was established, including determining the spacing between planes of atoms in a nanomagnet to determine its crystal structure as well as comparing

properties of nanomagnets with different elemental combinations.
*Keywords: nanostructures · magnets · nanomagnets · magnetic properties · HRTEM*

## Introduction

It has been shown that differences exist in properties between bulk material and the same material with nanosized dimensions. The alloy composition of bulk metals affects the characteristics displayed by that metal as can be seen in the different types of steels that exist. Simply by altering the alloy composition of the steel, properties such as strength, malleability, and ductility change. On the other hand, nanoalloy research has shown that properties of the same material on the nanoscale may be affected by many different aspects (Ferrando et al. 2008). Based on the desired results, there are specific alloy mixtures that yield compositions and sizes that show properties that are different from bulk material of similar make up. In fact there is also evidence supporting the belief that nanoalloys have compositions and sizes that yield results similar to different bulk materials. Certain sizes of nanoalloy clusters may be more suited to certain properties based on having similar crystal structures (Ferrando et al. 2008).

Being a nanoalloy, nanomagnets will change properties based on the alignment of their atoms, or crystal structure. The crystal structure may change configurations based on the process of creation as well as from the composition of the material. Because properties of materials change when atoms are aligned in different manners, knowing the crystal structure of nanomagnets and their resulting properties is a huge step in characterizing them.

In some studies, it has been shown that the L10 crystal structure (Figure 1) for nanoclustered alloys has high magnetocrystalline anisotropy, or naturally occurring differences in the magnetic field. The Iron-Platinum, FePt, alloy exhibits this property and is of special interest for its ability to resist temperature induced magnetic direction changes, or superparamagnetism (Klemmer et al. 2002). Anisotropy and superparamagnetism are only two properties affected by structure; indexing these properties (and many others) and their related structure will be quite useful in the production process.

To expedite this process, a method for indexing, or measuring, nanomagnet structures needed to be formed. One such method uses a

High Resolution Transmission Electron Microscope (HRTEM) to scan nanomagnet clusters. The HRTEM provides images at the nanoscale that show how the individual atoms of a material align together in layers. Utilizing this information, it is possible to calculate a 2D representation of a nanomagnet's crystal structure based upon its atomic structure.

## Objective

The purpose of this research is to develop a method in which an HRTEM image can be taken of any nanomagnet and produce the information needed to define its crystal structure. The procedure currently employs the image processing program ImageJ to analyze the images taken by the HRTEM (Rasband 2011). The experimental measurements can be compared with theoretical values to provide the closest matching crystal structure. Future research will include defining properties of nanomagnets based on their observed crystal structure.

**Figure 1**

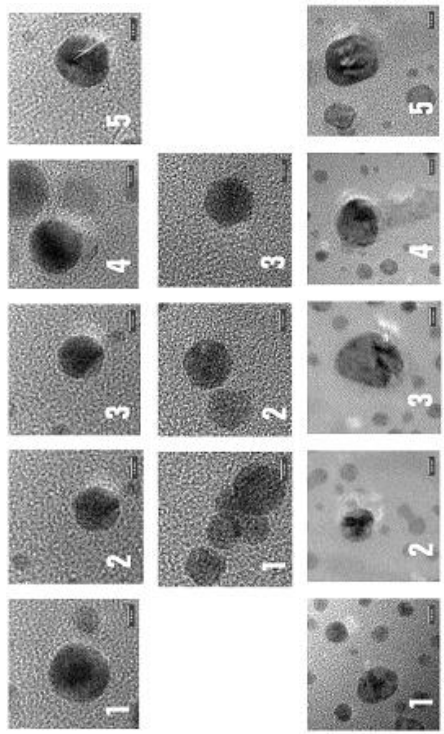


Figure 1: *Nanomagnet samples: FeAu (left column), FePt (center column) and MnAu (right column).*

## Background

*Images*

Images for our analysis were obtained using a high resolution transmission electron microscope (HRTEM). The HRTEM works by transmitting a beam of electrons through a thin sample, in this case a nanocluster (Figure 2). After the electron beam has transmitted through the sample and interacted with the crystal structure, the beam is focused through an electromagnetic lens and projected onto the viewing screen. The current state of the art HRTEM allows for a resolution as small as 0.047 nm. With resolutions on such a small scale, individual atoms can be viewed or imaged.

**Figure 2**

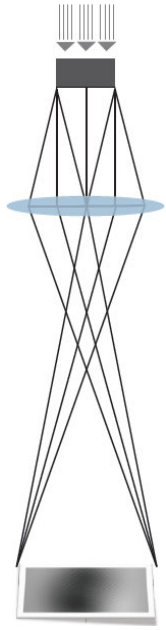

Figure 2: *Diagram of the inner workings of a Transmission Electron Microscope (TEM).*

*Fourier Transform*

The Fourier Transform is a formula that defines a wave by the summation of frequencies of periodic functions. The Fourier

Transform in physics is used as a compilation of frequencies at different amplitudes that define a wave. To simplify this, it can be compared to playing an instrument. A Fourier Transform of a musical chord would be all the notes that comprise it. In our use, the equation for the transform of some function is defined as:

$$F(t) = \sum_{i=1}^{n} a_n e^{2\pi i(\frac{n\,t}{T})}$$

where $T$ is the period and $a_n$ is the coefficient of the individual function. However, a Fourier Transform is time consuming and math intensive. Instead, a Fast Fourier Transform (FFT) can be performed using the ImageJ program (Rasband 2011). The results will be very similar but time is saved and human errors greatly limited.

A diffraction image based on interference is produced in a HRTEM during image formation. However, it is possible to access a mathematical copy by transforming the HRTEM image. The image's (FFT) illuminates the periodic nature of the nanomagnets, as would a diffraction image. On the atomic level, atoms reside in planes, which show periodicity. The FFT represents the inverse distance between these planes. Using this relationship, the FFT thus helped determine the distance between the planes in the crystal lattice.

*Proposed Structures*

For an alloy composed of two elements represented as variables and *Aa*, *Bb* the structures looked as follows:

**Figure 3**

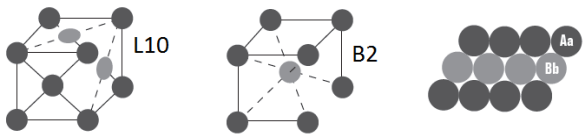


Figure 3: *Generic alloy structure.*

Therefore the calculated distances between planes of elements were of the square pyramid height $c$ , where $a$ is the atomic radius.

**Figure 4**

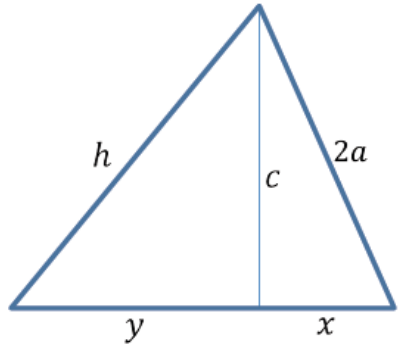


Figure 4: *Dimensions of atomic planes.*

**Figure 5**

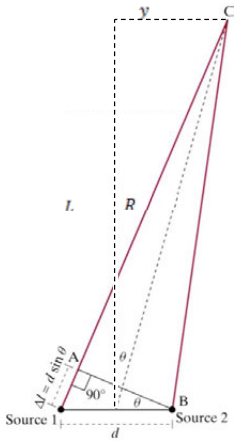


Figure 5: *Diagram of Bragg's Law, where* (L) *is the perpendicular distance between the slide/crystal,* (R) *is the straight distance from the slide/crystal to point* C, (d) *is the distance between parallel slits/planes,* $(\Delta l)$ *is the path length difference that wave* $AC$ *travels compared to wave* BC, $\theta$ *is the angle between the perpendicular line* L *and the straight line* R, $(\lambda)$ *is the wavelength of the electron/electromagnetic beam,* $(y)$ *is the between the screen center and* C *and* (n) *is the n'th maximum that* C *is from the screen center.*

*D-Spacing Equations*

Our calculations were based off of Bragg's Law, which is defined as :

$$n\lambda = 2d\,sin\theta$$

This equation comes from the diffraction triangle in Figure 5 where the leg is drawn so that it is equal to an integer number of wavelengths. This shows that when the two diffracted rays coming from two sources meet when they are in phase, constructive interference occurs and a maximum in the diffraction pattern is then shown on the screen at point. The relationship, then, is that when the actual diffraction pattern is projected, there is a direct relation from the pattern of maximums to the FFT.

The spacing represents the plane spacing in the material through which the wave is diffracted. This is the most essential element of this diagram. Using the HRTEM images, we were able to calculate the plane spacing of the sample.

*Plane Spacing*

The plane spacing is important because it describes the structure of the sample used to create the diffraction. On a molecular level, the plane spacing is relative to the size of the atoms in the structure, but their 'packing' can vary. This packing can affect the atomic spacing. This is important to determine because different plane spacings will yield different properties. To index the images, we compared theoretical plane spacings to experimental measurements. We made the following assumptions:

1. Crystal structures are either L10 or B2,
2. Like atoms form planes. Layers alternate. For example, Mn/Au/Mn/Au planes,
3. The structures can be modeled as cubic, to the first order, due to similarity in atomic radii for Fe, Au, Pt and Mn.

**Figure 6**

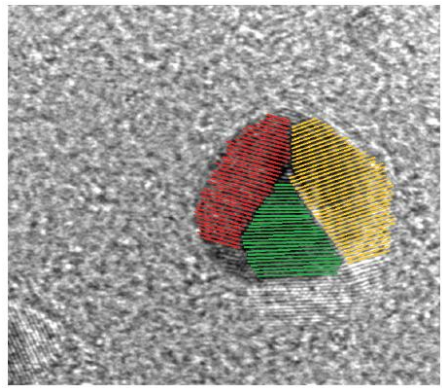

Figure 6: HRTEM image of FeAu nanomagnet. The colored lines are not a product of the imaging technique but were instead added to emphasize the multi-faceted nature of this particular nanomagnet.

**Figure 7**

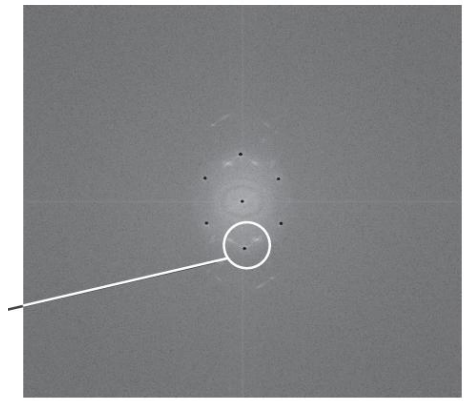

Figure 7: *FFT image using ImageJ*

**Method**

*Step 1*

First, we drew lines along rows of atoms and measured the perpendicular distance across them.

*Step 2*

Next, we took the FFT of the image and hovered our cursors over bright spots in Image J, revealing the real-space distance between the corresponding planes.

*Step 3*

Finally, we looked at the plot profile– Image J creates an intensity vs position plot from which peaks can be counted and measured– for each image.

**Figure 8**

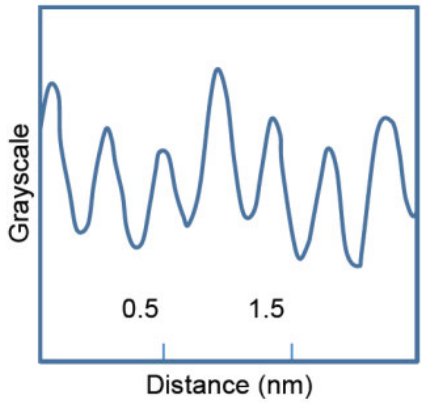


Figure 8: *Plot vs. Intensity graph of an HRTEM image of a nanomagnet using ImageJ.*

Since materials are 3-dimensional, there are many planes that cannot be drawn without multiple images from different angles of the particles. Planes are most often described by a set of three values which describe vectors in 3D space. These vectors identify three points which then form a plane. Almost any plane drawn through a homogeneous sample will yield a repeating

pattern of atoms. If one were to identify the structure in a sample, the pattern can be repeated to redraw the entire structure.

*Step 4*

Additionally, first and second order Brillouin Zones were performed on each image. An example of the Brillouin Zone analysis shows how first and second zones were formed. The sample FeAu 1 FFT is the nearest to a symmetric hexagon.

**Figure 9**

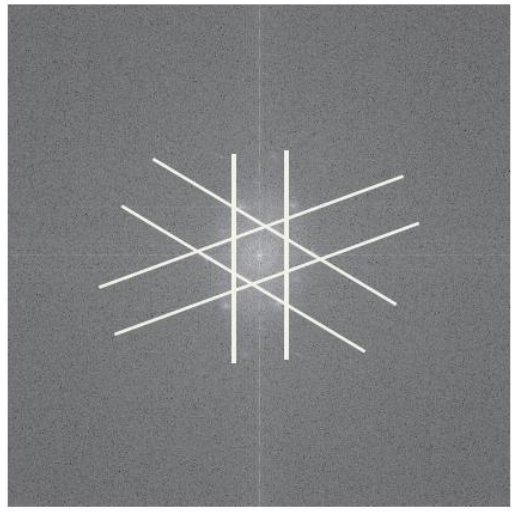

Figure 9: *First and second order Brillouin Zones of the FFT of the FeAu 1 nanomagnet.*

*Analysis of Nanomagnets*

The equation for distance of the plane was derived to understand the relationship between the various dimensions of the nanomagnet. The ImageJ program was used to analyze the image of the nanomagnet. Using basic geometry, the experimental and theoretical distance between planes was calculated for the nanomagnet. The experimental distance between planes was calculated by each research team member and averaged to be 0.201*nm*. The theoretical distance between planes of

cobalt and tungsten, being two atomic radii, was determined to be 0.27 *nm*. Since both cobalt and tungsten have nearly identical atomic radii, not knowing where each was in the image had negligible effects on the calculations. The reciprocal-space distance from the FFT center to the inner ring was calculated to be 2.2 $nm^{-1}$. The reciprocal-space distance from the FFT center to the outer ring was calculated to be 4 $nm^{-1}$.

## Results

After gathering the data, first and second order Brillouin Zones were performed on each images' FFT, shown in Table 1. Besides the FeAu 1 image (as shown in figure 9) the other first-zone hexagons were more distorted. This suggests one of two things: the viewing direction is not normal to the (111) plane or the viewed crystal face is a distorted version of the (111) plane. Table 1 documents the asymmetrical Brillouin zones through geometry.

**Table 1**

| FeAu 1 | FeAu 2 | FeAu 3 | FeAu 4 | |
|---|---|---|---|---|
| 0.204 | 0.208 | 0.211 | 0.219 | |
|  |  |  |  | |
| FePt 1 | | | | |
| 0.219 | | | | |
|  | | | | |
| | MnAu 2 | MnAu 3 | | MnAu 5 |
| | 0.206 | 0.191 | | 0.213 |
| |  |  | |  |

Figure 1: *Elemental composition of nanomagnets, their experimental plane spacing measurements and their brillouin zones.*

**Summary**

Experimental measurements of the plane spacing in FeAu, FePt and MnAu nanomagnets are in agreement with the theoretical plane spacing model. Measured Brillouin Zones show evidence that the observed plane is an FCC (111). Zones from some samples were inconclusive.

**References**

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