

# Characterizing Properties of Magnetic Films Deposited on Silicon Wafers

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*Silicon samples sputtered with multiple magnetic layers can be characterized by using x-ray diffraction (XRD), vibrating sample magnetometry (VSM), and magneto-optical Kerr effect (MOKE) techniques. XRD identifies the crystallographic structures and chemical composition of the unknown layers. VSM measures the change in magnetic moment versus applied field, thus giving the information needed to find film thickness. MOKE characterizes the many magnetic properties of the sample, including  $H_p$ ,  $H_k$ , and coercivity. Both, VSM and MOKE, are highly sensitive magnetometers and operate easily for electronic machines to date capable of quantifying both intrinsic and surface magnetization properties.*

## Introduction

Vibrating sample magnetometer (VSM) [15] and magneto-optical Kerr effect (MOKE) [16] are two complementary ways of defining magnetic properties of a layered silicon wafers through hysteresis loops. VSM observes magnetization behaviors from the top ferromagnetic layer through to the substrate layer of the silicon sample [10]. MOKE hysteresis loops often reflect complex magnetization properties, but is limited to the penetration depth of light [4].

Before determining magnetization properties, it is a common technique to identify the multiple layers of the silicon sample through x-ray diffraction (XRD). X-ray diffractometers are used to measure the material structure, chemical makeup, and layer grain size by recording the measured intensities as a function of  $2\theta$  [15]. For perfect crystals, the XRD graphs shows sharp peaks due to  $I(q)$  (the intensity as a function of charge) being proportional to true delta functions [6]. Imperfect samples show peaks with a widened base, and liquids have rolling peaks due to the consistently varying functions throughout the samples layers [2]. X-ray diffractometers take advantage of Bragg's equation ( $n\lambda=2d\sin\theta$ ) to generate the diffracting pattern of the sample. In the equation  $d$  stands for lattice spacing in nm,  $\theta$  is x-ray incident angle,  $n$  is the number of moles, and  $\lambda$  is x-ray wavelength in nm. As Bragg's law is met, constructive interference occurs from the lattice spacing and shows a peak [1].

The VSM determines magnetic properties throughout the sample by penetrating deep into the inner most layers previously characterized by the

XRD. This helps give a more uniform characteristic of the bulk material [10]. The VSM works by oscillating a magnet to induce a known voltage. The voltage vibrates the sample vertically at a measureable frequency. The induced voltage and resulting frequency gives the magnetic moment through Faraday's law [14]. The measured magnetic moment can then be used to find the thickness of the permalloy layers through the equation:  $m = (M)(V) = (M)(A)(t)$ .  $M$  is the magnetization of permalloy constant ( $\cong 800\text{emu/cm}^3$ ),  $m$  is the measured magnetic moment height of each loop divided by two, and  $V$  is the volume of the sample. In order to find the thickness of each layer measured, the volume must be converted to area ( $\text{cm}^2$ ) times thickness (cm).

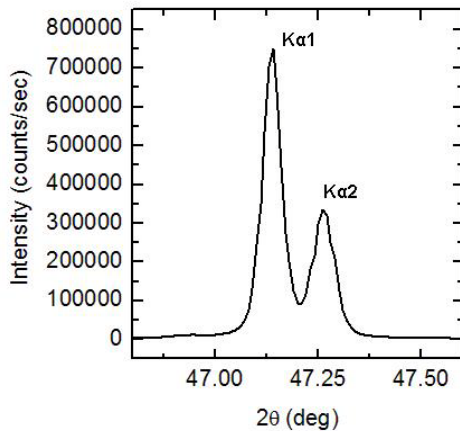
Unlike the VSM, the magneto-optical Kerr effect acknowledges the more complex nature of surface magnetism [7]. MOKE measurements show the change in the polarization of light as a function of applied magnetic field. The Kerr rotation is given as a complex function of wavelength, material, and film thickness [3]. This function is most importantly used to find magnetic coercivity of the sample [16]. Coercivity is defined as the magnetic intensity needed to demagnetize a substance that has been fully magnetized.

Unlike the VSM, MOKE is capable of measuring magnetic properties of only the top most layers in the sample. This is due to the use of light, which is only strong enough to penetrate through a small portion of the samples layers [4]. Due to the ability for the VSM to take measurements throughout the sample,

the results of the magnetic properties given by the MOKE and VSM can often differ [9, 11, 13].

### Experimental

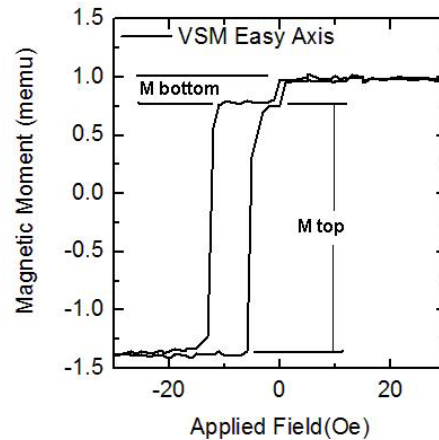
Films of multiple layers were applied to the Si(110) wafer by sputtering techniques. The first was a seed layer of Ni<sub>80</sub>Fe<sub>20</sub> with unknown thickness. The second is a Copper buffer layer with thickness of 100nm laid at 60 watts. Next is an anti-ferromagnetic layer of FeMn was deposited for 300sec at 60watts, making it a thickness of 30nm. Lastly was a magnetic layer of Ni<sub>80</sub>Fe<sub>20</sub> of unknown thickness. These layers were then further characterized with X-ray diffraction techniques. Figure 1 shows the XRD data graphed as intensity versus 2θ. The localization of the 2θ peaks characterizes the silicon substrate as (1,1,0). Due to the use of a Cu filter instead of a Ni filter, contaminate peaks are seen at low intensities.



**Figure 1:** XRD plot of intensity in counts per second vs. 2θ in degrees. The graph shows Si(1,1,0) Kα<sub>1</sub> Kα<sub>2</sub> splitting.

The silicon sample was run through the VSM after each layer had been identified by XRD. The VSM plot of magnetic moment (in memu) versus applied field (in orstedts) made two hysteresis loops, shown in Figure 2. The smaller loop corresponds to the magnetized Ni<sub>80</sub>Fe<sub>20</sub> closest to the silicon substrate; and the larger loop corresponds to the surface Ni<sub>80</sub>Fe<sub>20</sub> layer. The thickness of each layer can be calculated through the equation described in the introduction with  $M=800\text{emu/cm}^3$ ,  $m=m_{\text{top}}/2$  or

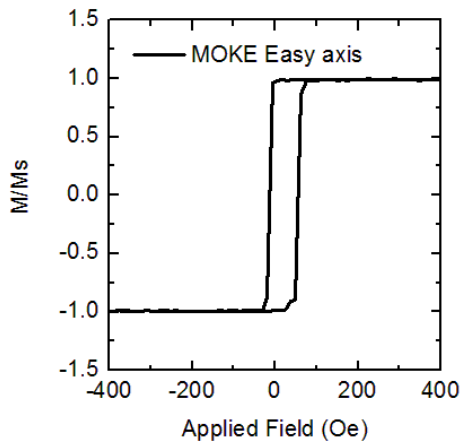
$m_{\text{bottom}}/2$ , and the area of the sample as  $0.5\text{cm}^2$ . The magnetic moment of the smaller loop ( $m_{\text{bottom}}$ ) is found to be  $0.0002\text{emu}$ , and the thickness of the first Ni<sub>80</sub>Fe<sub>20</sub> layer is calculated to be 2.5nm. The larger loop has a magnetic moment ( $m_{\text{top}}$ ) of  $0.0022\text{emu}$ , and thus a film thickness of 27.5 nm for the surface Ni<sub>80</sub>Fe<sub>20</sub> layer.



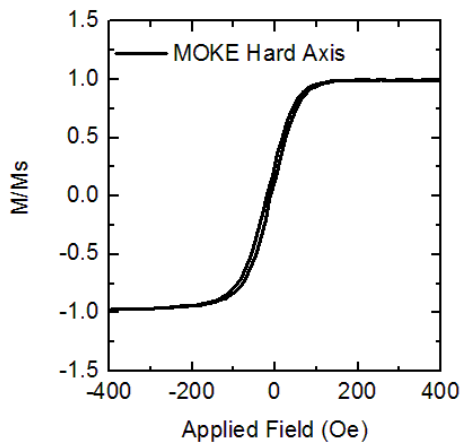
**Figure 2:** VSM easy axis of sample Si(110)/2.5nm Ni<sub>80</sub>Fe<sub>20</sub>/100nm Cu/30nm FeMn/27.5nm Ni<sub>80</sub>Fe<sub>20</sub>. The smaller loop corresponds to the Ni<sub>80</sub>Fe<sub>20</sub> layer adjacent to the silicon substrate, and the larger loop corresponds to the Ni<sub>80</sub>Fe<sub>20</sub> surface layer.

Using the MOKE technique on sample epsilon, hysteresis loops of easy and hard axis were found. The graph of the easy axis, shown in Figure 3, contains the properties of Hc and Hp. Hc denotes the amount of hysteresis in relation to coercivity of the sample [7] and is found by taking half the horizontal distance through the hysteresis loop. Hc is found to be 34 for sample epsilon. Hp is the distance from the horizontal midpoint of the hysteresis loop to the point where applied field equals zero. The difference here is due to the magnetization left on the sample after the removal of an external magnetic field [16]. This offset, Hp, is found to be 22 for sample epsilon. Properties like Hc and Hp have been found to have some interesting relationships to film thickness. Plots of Hc and Hp

versus the inverse of film thickness are linear when the anti-ferromagnetic layer is on top of the ferromagnetic layer [8]. Unfortunately, the silicon sample used has a ferromagnetic layer on the surface and therefore the linearity between  $H_c$ ,  $H_p$ , and inverse film thickness does not hold.



**Figure 3:** MOKE easy axis of sample epsilon plots M/Ms vs. applied magnetic field in Orstedts.



**Figure 4:** MOKE hard axis of sample epsilon plots M/Ms vs. applied magnetic field in Orstedts.

The MOKE hard axis graph of the sample epsilon, shown in Figure 2, portrays more information on the coercivity of the sample along with the value of  $H_k$ .  $H_k$  is the point on the hysteresis loop where increasing the applied field begins to have a reduced effect on the magnetic moment. For sample epsilon,  $H_k$  was found to be 81 by the 95% method, which

consists of finding the point of applied field where there is no longer and increase magnetic moment and taking 95% of that applied field.

### Conclusion

After analyzing the data receive from the different silicon wafer samples, VSM and MOKE show unique and complementary ways to characterize each samples properties. XRD first identifies the chemical makeup of each layer of the sample. VSM penetrates deep into the layers to give the information needed to calculate individual layer thickness. MOKE gives quick descriptive information on the magnetized surface layer of a sample, including coercivity. Overall, all three machines are sensitive and operate easily for electronic machines to date, quantifying both intrinsic and surface magnetization properties.

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