APT of Magnetic Thin Films

for storage, memory & spintronics applications

Magnetic thin films that have perpendicular magnetic anisotropy are now being used in data storage, magnetic random-access memory (MRAM), and spintronics applications. One means to achieve such perpendicular anisotropy is to exploit the interfacial anisotropy in many magnetic systems. By alternating layers of ferromagnetic and nonmagnetic thin films, large values of perpendicular magnetic anisotropy can be achieved and tuned by controlling the layer structure. One example of such a material is a multilayer comprised of alternating layers of $Co_{90}Fe_{10}$ and Pd.

Specifically, we investigate a structure where the $Co_{90}Fe_{10}$ and Pd were deposited by magnetron sputtering. Both transmission electron microscopy (TEM) and atom probe tomography (APT) characterization are used to provide a deeper understanding of the materials' microstructure. Figure 1 shows cross section a high angle annular dark field (HAADF) transmission electron micrograph of the sputtered $Co_{90}Fe_{10}$/Pd stack on a SiO_2 substrate with alternating layers visible [1]. Nanoscale non-planarity is visible in some layers, which can impact device performance. Atom probe tomography data can be used as a complementary technique that reveals the elemental distribution in three dimensions.

Isoconcentration surfaces of 60 at. % Pd and 40 at. % Co are shown in Figure 2a. In both the HAADF and APT data, roughness of the layers increases from the bottom to the top, showing that on the substrate the first deposited layers are significantly smoother than those deposited later. Figure 2b shows the tilt angle of the $Co_{90}Fe_{10}$ interface also increases as a function of the distance from the substrate, before leveling off. This progressive increase of tilting is due to the accumulated propagation of interfacial roughness during the sputtering process. This will result in local fluctuations of the coercivity over the planar device. Similarly, in MRAM, when millions of nanostructures are patterned out of such a material, each of them may have varying magnetic properties and therefore a distribution of critical currents is needed for device operation. Structural information provided from TEM and APT provides the feedback needed to optimize or develop a process for these materials and correlates magnetic properties to the microstructure.

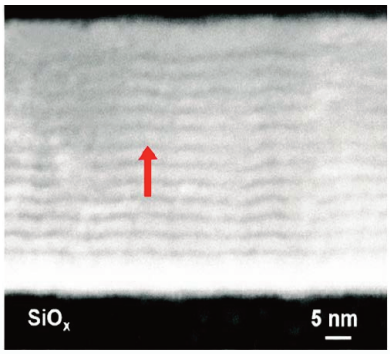


Figure 1:
HAADF image of sputtered CoFePd stack reproduced from [1]. The red arrow indicates the growth direction.

Figure 2a:
APT isoconcentration surfaces of Pd and Co showing propagation of layer roughness

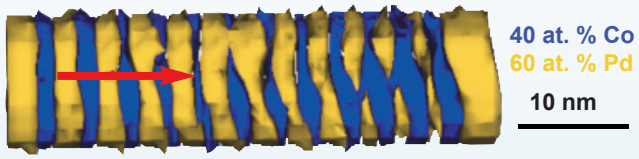
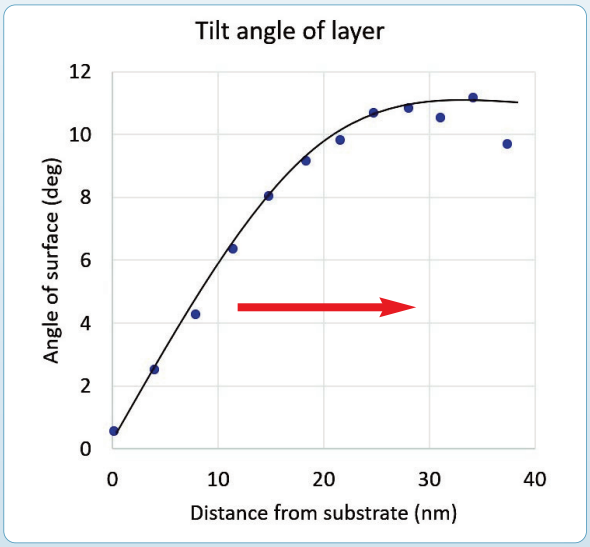


Figure 2b:
Tilt angle of the isosurfaces from the substrate.



[1] Zhang, D., Shaw, J. M., Smith, D. J. & McCartney, M. R. Domain structure and perpendicular magnetic anisotropy in CoFe/Pd multilayers using off-axis electron holography. Journal of Magnetism and Magnetic Materials 388, 16–21 (2015).

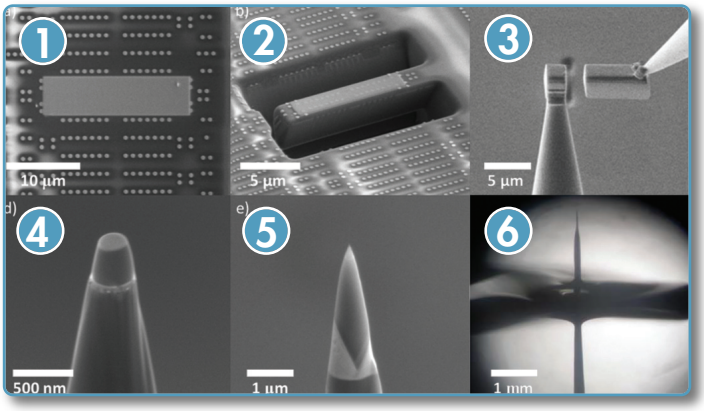
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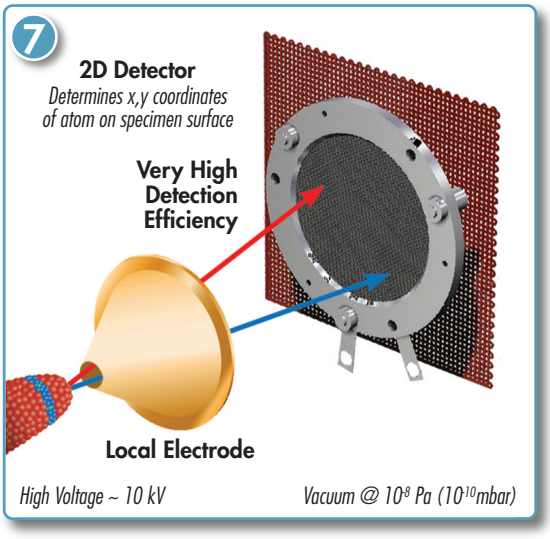
Three Steps to 3D Nanoscale Analysis

An Introduction to Atom Probe Tomography

Step 1: Specimen Preparation

An atom probe specimen usually has a nanoscale region of interest (ROI) requiring both 3D compositional imaging and analysis. The sample is formed into a needle shape containing the ROI. Common APT specimen preparation methods using electropolishing or a Focused Ion Beam system (FIB) are very similar to TEM methods except instead of forming a thin sheet, a needle shaped sample is desired. At the right, standard FIB liftout and mounting of a specimen (figures 1 through 3) and then sharpening the sample with the ROI left at the very apex (4 and 5). In 6, a wire geometry sample is being electropolished.





Step 2: Data Collection

An atom probe produces images by field evaporating atoms from a needle-shaped specimen and projecting the resultant ions onto a detector 7.

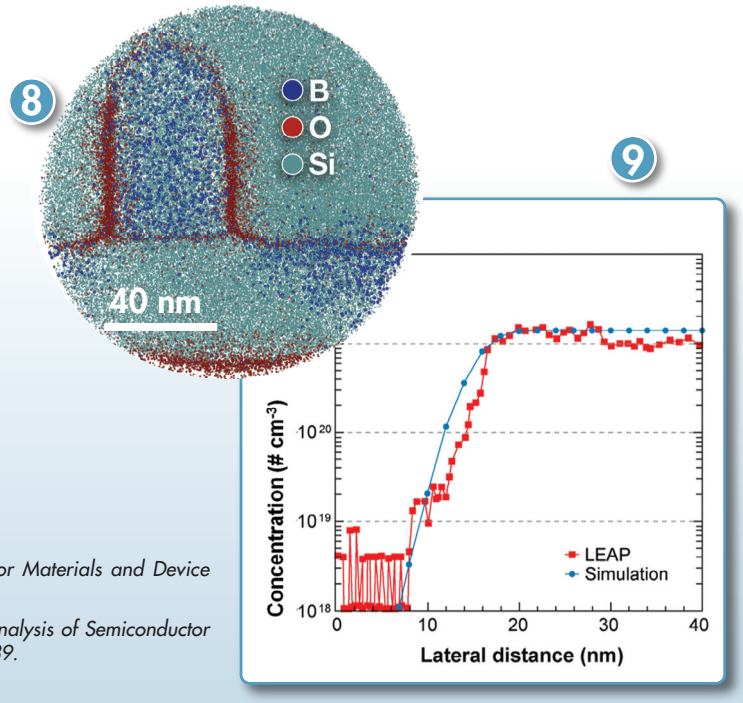
A high magnification results from the ~ 80nm tip being projected onto an 80mm detector resulting in a magnification of approximately 10^6.

An atom probe identifies atoms by their mass-to-charge-state ratio *(m/n)* using time-of-flight mass spectrometry. Charge state, *n*, is typically 1 to 3.

The specimen is held at approximately 50K to reduce surface diffusion during the experiment. The high electric field results in 100% ionization and the high speed detector is capable of measuring up to 80% of the collected ions, independent of ion mass.

Step 3: Data Visualization and Analysis

Examples of data output are illustrated by a slice of a 3D atom map of a transistor† 8, and a dopant composition profile‡ 9. The image shows the positions of individual atoms (oxygen is red and boron is blue) in the transistor with subnanometer resolution. From the reconstructed data set many types of useful analyses are possible. These include 3D visualization, 2D atom mapping 8, 1D depth profiling and line scanning 9, as well as mass spectra and compositional analysis from user-selected volumes.



† *Lauhon, L. J. et al, MRS Bulletin "Atom Probe Tomography of Semiconductor Materials and Device Structures" 34(10) (2009) 738.*

‡ *Moore, J. S.; Jones, K. S.; Kennel, H.; Corcoran, S., Ultramicroscopy "3-D Analysis of Semiconductor Dopant Distributions in a Patterned Structure using LEAP" (2008), 108, 536–539.*

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