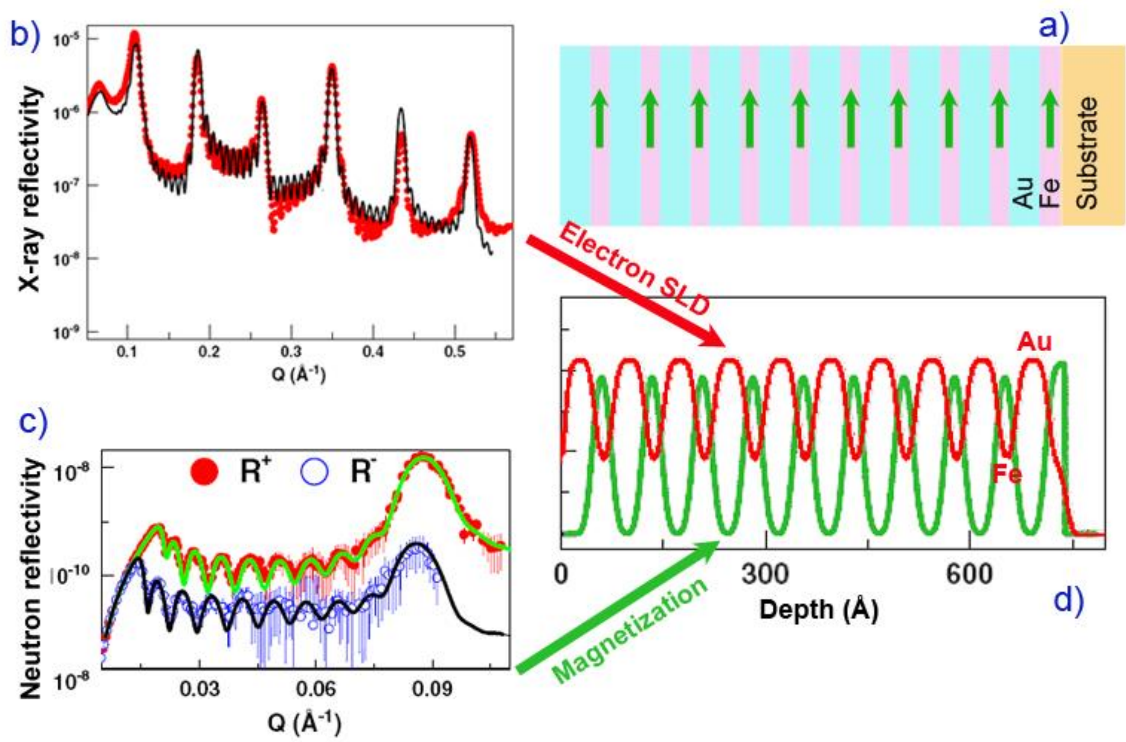
Uncovering the magnetization of nanolayers in magnetic devices

Artificially structured magnetic thin films or multilayers in the nanometer range play a vital role in computer memory applications, and are also of high fundamental scientific interest. Albert Fert and Peter Grünberg discovered in 1988 the Giant Magnetoresistance (GMR) effect, for which they were awarded the Physics Nobel Prize in 2007. In this effect, a system composed of alternating layers of magnetic and non-magnetic conductive layers, of nanometer or sub-nanometer width, undergoes a large change in electrical resistance when subject to an external magnetic field. The same occurs in the Tunneling Magnetoresistance (TMR) effect, in which the non-magnetic layers are electrical insulators. In both cases the effect is due to interaction of the magnetic layers through the non-magnetic layers, and is critically dependent on the magnetization and thickness of each layer.

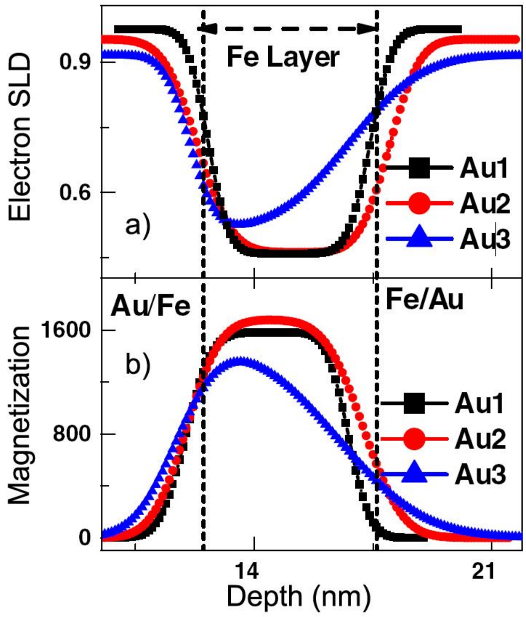
The technological importance of GMR and TMR was immediately recognized: these new nanostructured magnetic materials could be used to detect very small magnetic fields, which is essential to read data in hard disk drives and other devices. Modern high density magnetic recording would not be possible without very sensitive magnetic field sensors. In 1997, GMR read heads started to take over traditional systems in commercial applications, and in 2004 TMR read heads were introduced. Another application is in magnetoresistive random-access memory (MRAM), a non-volatile random-access memory being developed as an alternative technology for hard disk drives.



a) Schematic Fe/Au multilayer. The green arrows depict the Fe magnetization b) X-ray reflectivity data. c) Neutron reflectivity data. d) The electron scattering length density (SLD, in red) reflects the electron density, and distinct Au and Fe layers are observed. The magnetization (in green) occurs in the Fe layers only.

Figure credit: Adapted from [Surendra Singh et al., 2014.]

GMR and TMR depend critically on each layer's magnetization state, as well as on interfacial roughness and structure. Polarized neutron reflectometry (PNR) is the technique of choice to study the magnetization of individual nanolayers in multilayered systems. Dr. Surendra Singh and co-workers from the Bhabha Atomic Research Centre in Mumbai, India, studied the role of interface structure and magnetism in magnetoresistance (MR) in Fe/Au multilayers, where iron (Fe) magnetic layers had thickness from 3 to 10 nm, and the gold (Au) layers had thickness from 5 to 15 nm (S. Singh et al., 2014). The interfacial structure was determined with X-ray reflectivity. In combination with PNR, a detailed depth profile of structure and magnetism in the layers was obtained.



a) Chemical profile (electron SLD) from X-ray reflectivity data. b) Magnetization from polarized neutron reflectivity data. Au1, Au2 and Au3 denote multilayers with 5, 10 and 15 nm gold layer thickness.
Figure credit: Adapted from Surendra Singh et al., 2014.

They observed that the magnetization in the iron layers comes from the chemical density profile at the interfaces and lowering interface roughness results in higher magnetization of the Fe layer. The sharper interfaces also resulted in higher magnetoresistance values, which is a well-known phenomenon. However, Singh and co-workers observed asymmetric interfaces, and a corresponding asymmetry in the magnetization, with an extraordinary depth resolution. Higher asymmetry in structure and magnetization at the interfaces was correlated with decreasing magnetoresistance. Controlling the growth mechanisms that lead to asymmetric interfaces is one step towards better performance of GMR and TMR devices.

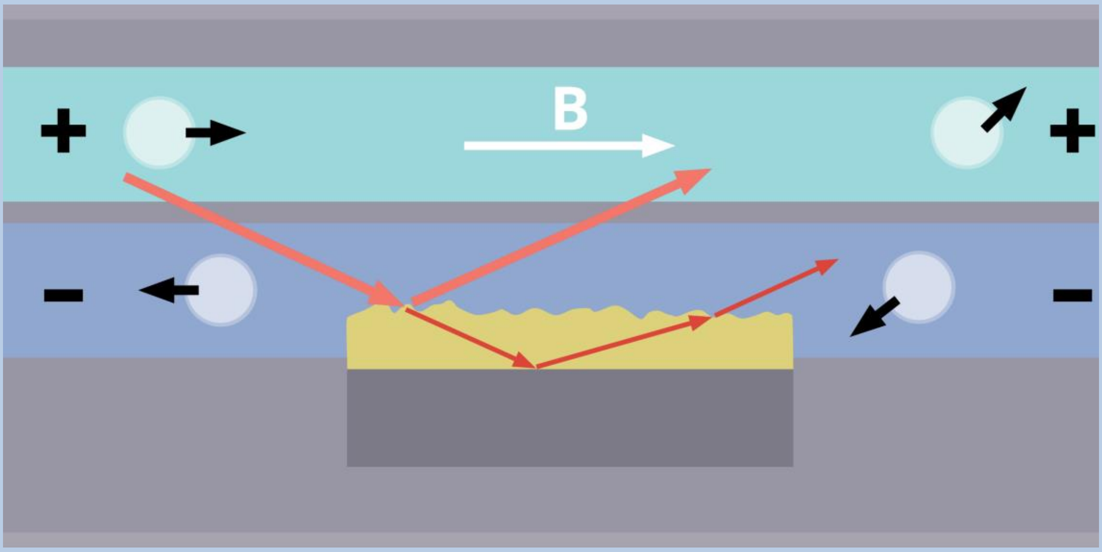
What is Polarized Neutron Scattering?

Polarized neutron scattering is one particular variant of neutron scattering, which encompasses a group of techniques based on impinging a neutron beam on a sample and detecting the neutrons that come out, either reflected from the surface or after interaction in a deeper layer.

In neutron reflectometry, the neutron beam incises at grazing incidence, and the interaction occurs in the sample near-surface. Surfaces and interfaces are then characterized at the nano-scale. Changing the neutron energy and the detection geometry, different scales can be accessed and studied, from a few nanometers to a fraction of a millimeter.

In all samples, the nuclear interaction between the neutrons and the sample nuclei leads to scattering. In a magnetic sample, there is an extra interaction, because neutrons have a magnetic moment. The direction of the neutron's magnetic moment is defined by its spin, which can be "up" or "down", i.e. aligned parallel or antiparallel with an applied magnetic field. The interaction with magnetic layers is different for spin "up" and spin "down" neutrons.

Neutron beams are normally not polarized, which means that they have an equal amount of neutrons with spin "up" and spin "down". Polarized Neutron Scattering is based on creating a polarized neutron beam, that is, with either only spin "up" or only spin "down" neutrons. The reflected beam intensity will depend strongly on the magnetization of each layer. Typically, experiments are made for both neutron spins. The magnetization state of individual layers can be determined, often with nanometer resolution.



The magnetization state of a magnetic system is commonly determined with magnetometers - normally a vibrating sample magnetometer or a superconducting quantum interference device (SQUID), or using the magneto-optical Kerr effect (MOKE). The measurements usually take the form of hysteresis loops, in which the total magnetization of the system is measured as a function of an applied field. While a great deal of information is obtained from such measurements, it is always the total magnetization that is determined, and not that of individual layers. Furthermore, when different layers have magnetizations that form an angle to each other, the hysteresis loops may be difficult to interpret. Polarized neutron scattering overcomes these limitations, and is then the technique of choice in the complex multilayered magnetic systems that are used in many electronic devices.