Dr. Saeed Kamali

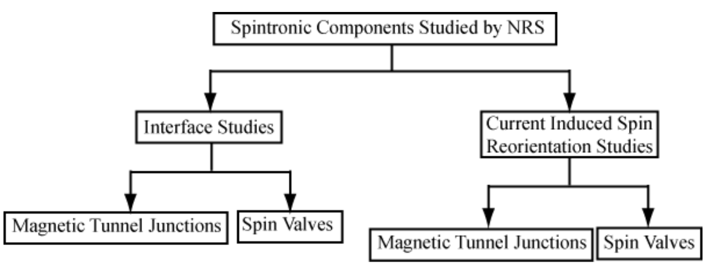
Statement of Research Interests and Proposed Activities

I have an independent research program consisting of several projects within nanoscience fields using laboratory as well as synchrotron-based techniques to study different aspects of individual project; i) interface and magnetic studies on layered structured used in spintronics such as Fe/Cr, MRAM/MTJ and Exchange Spring Magnets; ii) Studies on common properties of self-assembled and superlattices of magnetic nanocrystallites of iron-oxides and spinels that play vital roles for the functionality, such as superparamagnetism, exchange interaction between particles and dispersivity; iii) Magnetic and structural properties of magnetic and non-magnetic nanoglasses.

Some of these projects are described in more detail below:

A) Nano-manufacturing, Interface Studies and Current Induced Spin Reorientation in Magnetic Tunnel Junctions and FePt-based Spin Valves by Nuclear Resonant Scattering

Specific aim: In this project, I will nano-fabricate Magnetic Tunnel Junctions (MTJs) and spin valves over large areas and their magnetic and electronic structures will be studied by synchrotron and laboratory techniques. MTJ is the main component in Magnetic Random Access Memory (MRAM), consisting of two ferromagnetic thin layers separated by an oxide insulator thin layer. In spin valves, which are used in magnetic read head, magnetic storage media and magnetic sensors, non-magnetic metallic layer is used instead for oxide insulator. In the first part of this project interface quality of MTJs and spin valves at both interfaces will be investigated. The interface quality between the magnetic layers and the insulator layer plays a fundamental role in the tunneling of electrons between the magnetic layers and hence the value of the Tunneling Magnetic Resistance (TMR) in MTJs respective Giant Magneto-resistance (GMR) in Spin valves. The increase of TMR and GMR has been the main focus of field of spintronics in the past two decades. As Nuclear Resonant Scattering (NRS) is a technique that gives information at the atomic level that is, for Fe, only sensitive to the ^{57}Fe isotope, its use in this study combined with isotope specific labeling will be a strong approach to study the interfaces. These results will be combined with theoretical studies to give a relevant picture of the physics in both systems. An important aspect in this project is to study homogeneity of the structures when these compounds are grown on large substrates for nano-manufacturing. The substrates will be cut into smaller pieces for studies of the magnetic and electronic properties thus establishing if all parts of these large trilayer structures have the same magnetic properties.



The second part in this project concerns the current–driven reorientation of spins in MTJs and spin valves, which due to high current density of 10^5-10^7 A/cm^2, requires a nanometer scale in lateral dimension of these components. The advantage of NRS is the exact determination of magnetization direction in the plane of the film as a function of the current. Due to the small size of such components for applications, a large number of such components will be grown on a larger substrate and then cut into small pieces. The structure of the different parts of the proposed studies is summarized in the chart (left).

Project Introduction

1) Interface Studies by Nuclear Resonant Scattering: In this subproject the lower and upper interfaces; specifically the interface between lower electrode and the spacer layer and the interface between the spacer layer and the upper electrode, will be studied by introducing thin ^{57}Fe at interfaces and performing NRS, resulting in signals just from these specific parts of the samples. The systems studied will include:

1.1) Magnetic Tunnel Junctions: Magnetic Tunnel Junctions, which are the core element of the MRAM [1]**,** will be studied to determine the oxidation state of Fe at the two interfaces as a function of oxidation conditions, barrier thicknesses and anneal times.

1.2) Spin Valves: Spin valves are interesting devises in spintronics with many applications. There are a lot of interesting effects occurring in such systems. An important effect is the GMR effect, where electrons with different spin directions experience different potential barriers in passing from one ferromagnet to another via the spacer layer. In case of parallel alignment of the magnetic layers, there is high conductivity for one spin direction, hence high conductivity. In case of anti-parallel alignment, both spin directions will experience high barrier potential and hence low conductivity.

Proposed Project: I propose growing FePt-based spin valves with FePt alloy as lower electrode, NiFe alloy as upper electrode and Cu as spacer layer by means of sputtering or MBE. I will deposit thin ^{57}Fe layers at either the lower interface as well as upper interface to study both interfaces separately.

2) Current–driven reorientation studies by Nuclear Resonant Scattering

Another approach in application of MTJs and spin valves is the current–driven reorientation of spins, which was theoretically predicted in 1996 by Slonczewski [2]. Katine *et al.* [3] have shown experimentally that magnetization switching can be induced by spin-polarized current. It was also demonstrated that the reorientation of spins in devices containing multilayers of magnetic-nonmagnetic layers does not require the application of an external magnetic field. The re-orientation of spins can be achieved just by passing an electrical current through the magnetic layer. Spin-transfer switching demonstrated in multilayers consisting of magnetic and nonmagnetic layers is very promising for advanced MRAM applications.

2.1) Current-driven reorientation of spin in Magnetic tunnel junctions: Until now, the observation of spin transfer switching is mainly based on macroscopic methods such as resistivity measurements. A detailed insight into the local magnetic properties can be achieved by NRS measurements. The aim of the measurements is to understand the behavior of the magnetic moment as a function of current, i.e. to measure the magnetic hyperfine field (B_{hf}) distribution and the orientation of B_{hf} as a function of applied electrical current.

Proposed project: We propose two similar MTJ systems as follows: a) Fe (100)/MgO/Fe(100)
b) FeCoB (amorphous)/MgO/FeCoB (amorphous). Achieving switching current density 10^5-10^7 A/cm^2 is the most challenging issue for the application of the spin transfer switching. Therefore, the observation of the spin-transfer-effect requires a low dimension of sample (0.5 x 0.5 mm^2) and the limited thickness of ^{57}Fe, ~5 nm, resulting NRS to be the only suitable method for this work.

2.1) Current-driven reorientation of spin in spin valves: The reorientation of spin can also be performed by electric current in spin valves. Spin valves, which contain alternating nm-scale thick layers of magnetic and nonmagnetic layers such as CoFe/Cu/Co will be studied in this subproject.

Proposed project: For the observation of spin momentum transfer switching, FeCo/Cu/Co Multilayers are prepared in the geometry suggested by Slonczewiski [2].

Background: Preliminary Results and feasibility: While the MTJ oxidation process and the composition at the bottom interface has been studied in the past using various spectroscopic techniques, no attempt has been made to use NRS, for studying the above-mentioned spintronics components. This project will hence be the first to report on the quality of the MTJ and spin valve interfaces as well as current-driven spin reorientation in these components by NRS and MS.

Significance: The development of applied spintronic technology is one of the hottest scientific fields in the world. Two results of this technology are MRAM and spin valves, which will play crucial role in the microelectronics and data storage industry. It will be extremely valuable to use NRS to extract as much information as possible about the nature of Fe in these components. The interface structure in these systems is of paramount role in determining their magnetic properties. Other new phenomena with industrial applications, such as non-collinear magnetic exchange interaction between Fe layers depend on the defects, steps, roughness and intermixing at the interfaces. This is why the understanding of the interfaces is very important in designing the spintronic devices. Techniques such as X-ray diffraction are just able to give an average roughness in the whole sample and most of the other techniques may in the best case give indirect information on the atomic scale about the interfaces. Due to the monolayer resolution, NRS is a powerful technique to study interfaces in spin valves. The current-driven spin reorientation in these systems is also very important issue to be studied to get information about orientation of B_{hf} as a function of applied electrical current.

B) Self-Assembled and Superlattices of Nanoparticles

Crystallites in nanometer sizes, termed nanocrystallites (NCs), are another important class of nanostructured materials. In this class of material, the electronic structure is described in discrete electronic energy levels, hence many properties are different compared to bulk materials. Lowering of melting points, electron confinement, surface plasmon resonance and quantum-well effect are some characteristic phenomena for nanoparticles. These and other interesting properties make NCs very capable for industrial applications such as in catalysis, electronic devices, high-density storage magnetic tapes and even in medical applications. Among different kind of NCs, due to novel properties, iron oxide NCs have various applications in different fields, from new functional materials such as magnetic recording media [4] to biomedical diagnostics and therapy such as cancer treatment by hyperthermia [5]. For applications, especially in medicine, for example in cancer treatment, the monodispersity and the knowledge of the magnetic properties are crucial. The size and shape of the NCs can be controlled during the chemical synthesis.

Furthermore, to be able to use these nanostructures in devices in applied nanotechnology, the construction of superlattices of such nanostructures is very important. The self-assembly of nanoparticles to superlattices, which are observed in biological system such as biomineralization [6] and geological systems such as ancient paints [7] has been prepared in the form of iron oxide super crystals [8]. Such supercrystal or superlattices, i.e. ordered arrays in micrometer ranges are used for example in constructing high-density storage media [9, 10] and band-gap of semiconductor quantum dot arrays [11]. It is worth mentioning that most of the studies until now concerns self-assembly of spherical nanoparticles, where they form hexagonally packed arrays. Unfortunately, there has not been much experimental work on self-assembly of ordered arrays, especially in three-dimensional structures, of nonspherical NCs. Although the thermodynamic parameters and also the external electric and magnetic fields during the production of structures of superlattices of NCs are important, the shape of the NCs is the crucial element in dictating the symmetry of the array. In a recent study [12], we showed for the first time that cubic NCs could assemble into a highly ordered body-centered tetragonal structure. Another important aspect in self assembled NC, which has not been explored, is the easy axis of the magnetization of the building blocks of self-assembled of NCs. As this parameter is of crucial importance in industrial applications, an understanding of its behavior in an external magnetic field and the underlying physics is very important.

Proposed project: The oleic acid capped cubic and the spheroidal iron oxide NCs will be synthesized by thermal decomposition of an iron (III)-oleate complex. The oleate precursor is prepared according to a previously described method [13]. The spheroidal nanoparticles are produced in a regular reflux apparatus whereas the cubic particles are produced by attaching a Dean-Stark condenser, allowing volatile by-products to be removed during the decomposition reaction. The preliminary data of MCS show that the preferential magnetic easy axis is different between the self-assembled of spherical NCs and cubic NCs deposited with no external magnetic field. To prepare two and three dimensional long-range order and macroscopic dimensions of magnetic nanoparticle arrays a modulated magnetic field can be used [14]. The particle concentration and the duration of the applied magnetic field are two important factors in controlling the dimension of such superlattices. Applying the magnetic field during the initial phase of drying will result in thin arrays of superparamagnetic nanocubes with high degree of orientation. By extending the duration of the magnetic field to the whole assembly process the micrometer-sized and thick three-dimensional mesocrystals are obtained. Though, as mentioned before, the nanoparticles in this size range are superparamagnetic, i.e. the magnetization direction of each nanoparticle fluctuates randomly at room temperature and as the consequence of that they cannot be used in magnetic storage media, an ordered array of such nanoparticles might be suitable candidates for such purpose.

Assemblies of NCs with different shapes will be deposited on clean germanium substrate by spin coating of toluene dispersed of NCs. A static field of ~30 mT perpendicular to the substrate will produce highly ordered mesocrystals. High Resolution TEM and X-ray diffraction will be used for characterization of the samples. MCS, which can measure spin-polarized electron momentum density distributions, is a powerful technique to probe magnetic atoms and magnetic NCs to study the preferential magnetic order for such assemblies. Furthermore, we will produce such NCs enriched in ^{57}Fe to be able to perform NRS to study the response of the NCs magnetization to magnetic external field.

C) Nanoglasses

Nanoglasses are glasses with a novel microstructure [15]. They consist, by analogy to a nanocrystalline materials, of nanometer-sized regions with a glassy structure. The electronic structure as well as mass density, make this class of material very important not only from a fundamental point of view but also for industrial applications. In these materials adjacent glassy regions are joined together by interfaces. The atomic structure of these interfaces is characterized by an enhanced free volume. The interfacial thickness is in order of a few interatomic spacing i.e. typically 1 nm or less. Nanoglasses are produced by evaporating glass-forming materials e.g. $Pd_{40}Ni_{40}P_{20}$ in an inert gas atmosphere so that glassy droplets with a diameter of few nanometers are formed.

These droplets are subsequently consolidated at pressure of up to 3 GPa in ultra-high vacuum. The resulting material is called a nanoglass. So far, nanoglasses have been prepared for a variety of chemical compositions (Fe-Si, Au-La, La-Si, Ni-Ti, Ti-P, NiPdP, Fe-Sc). The results of structural studies performed by WAXS, SAXS, Mössbauer spectroscopy, DSC and TEM experiments as well as MD calculations may be summarized as follows:

- Nanoglasses consist of nanometer-sized glassy regions joined by interfaces between these regions.
- The density in these interfaces is reduced in comparison to the one of a melt-spun glass with the same chemical composition- as well as in comparison to the density within the consolidated, glassy spheres.
- The Debye Temperature (T_D) of the interfaces is reduced relative to T_D of the consolidated glassy spheres.
- If the annuluses are annealed, the interfaces delocalized in the sense that the width of the region of the reduced density increases. Hence, the reduced density of interfaces that was initially localized to a few nanometers smears out over a broader region the thickness of which increases with annealing time.

The described modification of the vibrational spectrum of a nanoglass (relative to a comparable glass produced by melt-spinning) seems to be a characteristic fingerprint of a nanoglass, Moreover, the variation of the vibrational spectrum will affect significantly all glass properties that depend on its vibrational modes (e.g. the thermodynamics, the critical temperature of superconductivity, the curie temperature, the internal friction etc.). They are due to the nature of nanoglasses and also due to the smaller number of nearest neighbors (nn) and next nearest neighbors (nnn).

Proposed Project: We propose preparing different kinds of nanoglasses with emphasis on FeSc with different chemical compositions and different preparation routes. We will use different techniques to investigate the physical properties of them. Nuclear Resonant Vibrational Spectroscopy will perform to reveal differences in vibrational modes as a consequence of the strength between atoms in the single nanoglass particle. This strength is in turn function of the number of nn and nnn and distances to them. Another interesting synchrotron technique is High Energy X-ray Diffraction (HE-XRD), which gives the radial distribution functions revealing the distances to nn and nnn. This gives information which vibrational modes are more probable. We also anticipate being able to "see" if there is any long-range order existed between the nanoglass particles. Due to this possibility and also the shorter distances to nn and nnn, the magnetism should have very different characters in such structures. MCS will be used to reveal the nature of the 3*d* and 4*s* electrons. Furthermore, due to the glassy structure of such samples, we believe that the magnetic moment orientations should be very unusual. Hence, we will also perform NRS to investigate the magnetic behavior of such samples, especially in external high magnetic field, as magnetic moment orientations will be highly affected not only due to the interface effect but also due to the interaction between nanoglass particles and also to investigate the physics behind the probable long-range order.

As nanoglasses are materials which have not been well studied but will almost certainly play critical roles in future industrial applications, these studies will open new opportunities for scientists working in this field.

Other Projects: I have other projects as listed below:

Half-Metals: Since the review article published in Science by Wolf et al. in 2001 [16], indicating the possibility of applying electron spin alone or in combination with electron charge for future applications, there has been a huge amount of work on this issue. The interest for this field has been increasing since the application in industry became obvious [17]. I have two related projects on half-metals. The first one is on thin films and on multilayers of Huesler compounds with general formula X_2YZ, where X and Y are transition metals and Z is an element from III-V groups. These are one of the few classes of materials with 100% spin-polarized at the Fermi Level. The second project is Si-based half-metallic compounds, which can be used in spintronic field. They can be produced due to the well-developed semiconducting industries, and especially the Si industries, which are the most, mature ones. Practical realization of this idea will be a major breakthrough in the spintronic field. A promising compound is introduction of a single layer, a so-called a delta layer, of a transition metal element (TME), such as Fe, Mn or Co in to a Si thin film to achieve a digital ferromagnetic heterostructure. As spin is the most important parameter in spintronic components and as MCS measures only spin magnetic moment and not the orbital magnetic moment, this powerful technique will be use to study the spin moment in the above-mentioned structures. Also, single monolayer or sub-monolayer ^{57}Fe -and probably other Mössbauer isotopes- will be buried in a Si thin film to study the magnetization behavior by NRS.

Magnetic spinels: Spinel ferrite nanoparticles with the general formula MFe_2O_4, where M is a 3*d* transition metal, are very important materials and have been studied intensively due to their potential applications in for example high-density magnetic recording, microwave devices and magnetic fluids. The application of such materials is mainly due to very interesting magnetic and electrical properties, which are changed drastically by substituting Fe atoms in the magnetite, Fe_3O_4, by different kind of 3*d* transition metals (TM) with different valence values and also different magnetic properties. The doping elements will substitute the Fe cations. By introducing 3*d* transition metals in magnetite, one hopes to manipulate and control these magnetic and electrical properties. These samples can be produced by different techniques such as chemical routes and mechanical milling. Several parameters, depending on the production technique, dictate the cation distribution of 3*d* TMs; temperature, time, agent concentrations, etc. MCS, EXAFS, NRS will be used to study the magnetic and electronic properties of such samples.

Techniques:

i) Nuclear Resonant Scattering: NRS is the Synchrotron Radiation-based Mössbauer spectroscopy (MS). MS is a unique method in the sense that it provides local information at an atomic level about the magnitude of the Fe atomic. This technique will be used as a complementary technique to NRS in this project. Synchrotron radiation, due to its novel properties, is a proper source for studying nanostructured materials. The development of different synchrotron-based techniques enables us to perform measurements, which have not been possible before. NRS is now a routine technique for studying many different kinds of samples.

ii) Magnetic Compton Scattering: Magnetic Compton scattering (MCS) can measure spin-polarized electron momentum density distributions (called magnetic Compton profile (MCP)) and is a good probe of magnetic atoms. It is well known that the shape of MCP of a magnetic atom depends on its local atomic configuration or crystal direction.

Complementary Techniques: Because the use of the samples is so delicate, there will be place for complementary techniques such as XMCD, X-ray techniques, EXAFS and etc., some of which will be done in collaboration with other Universities and research centers.

Equipment, sample preparation and collaboration: For performing the Synchrotron-based measurements, there will be collaborations with ESRF in France, APS in the US and SPring-8 in Japan, where I have been performing my research during the last few years. My collaborators include workers such as: Dr. J. Åkerman, a recognized name in spintronic industry; Prof. K. Kovnir a well-experienced researcher in superconductivity and low-dimensional magnetism; Prof. M. Andreeva, a well-known scientist in NRS; Prof. Arun Bansil and Prof. Bernardo Barbiellini, world-wide recognized theoreticians in magnetism; Dr. Y. Yoda, a well-experienced scientist in NRS, Dr. Y. Sakurai, one of the most famous names in MCS; Prof. Pieter Stroeve, an established researcher in field of nanocrystalline materials; Prof. Herbert Gleiter, a world-renowned scientist in nanoglasses, as well as many others. The equipment needed for both the fabrication of the devices and the complementary measurements are available through collaborations at several Universities worldwide, such as UC Davis, The Royal institute of Technology (KTH) and Karlsruhe Institute of Technology in Germany.

Intellectual merit and Broader Impact: A complementary educational plan will develop a program to stimulate critical thinking, create hypothesis driven research projects and apply their learning to discovery - involving students of the University as well several high schools in the neighborhood. The program will include regular involvement of graduate, undergraduate, as well as postdoctoral researchers in research, delivery of lectures on nanotechnology in high schools with live demonstrations, and an outreach to the students of high schools in predominantly underprivileged and socio-economically impacted neighborhoods.

Educational Component: For the proposed activities we will leverage the on-going educational efforts and the existing or former educational experiences of mine as the PI. Briefly, I will work at educating students into critical thinking, create hypothesis driven research projects and apply their learning to discovery. We will provide independent research opportunities to traditionally underrepresented students. I will educate students to understand the role of graduate school to creating educational pathways towards successful careers. I will demonstrate the significance of multidisciplinary and collaborative approaches in today's society. I will collaborate with outreach programs having ties to local high schools to expose students and teachers to cutting edge engineering technologies. I will continue to employ High School Students in our laboratories. We will develop a freshmen seminar, open to all disciplines, which will focus on the nanoscience. I will develop a number of science and engineering courses and Freshmen Seminars.

Graduate education: In connection to this proposal, several graduate students will be engaged, in addition to a few undergraduate students. They will be engaged both at the laboratory activities and also will be introduced to synchrotron activities. They will have the opportunity to learn about cutting edge techniques and fields. In collaboration with the collaborators in Europe and the US, the students will get the chance to spend some time at the European and American research centers, where they will acquire expertise in growth and characterization of spintronic devices as well as other components in connection to my research activities. I will introduce student seminars about synchrotron, spintronics, nanoscience and characterization techniques.

In order to familiarize the students with scientific investigation methods, our graduate students will conduct uncomplicated experiments in our labs in the teaching section of the nanofabrication facility at the department. The experiments will include patterning wafers with photolithography; coating samples with thin dielectric, conducting or insulating films, performing film characterization and understanding the origin of film color variation; etching patterned wafers with RIE, SEM imaging or sensing nanowires. The students will also attend our research group meetings and present their scientific experience every quarter.

Involvement of Undergraduate and Visiting Students: The proposed research will be realized through hands on training processes of graduate as well as undergraduate students over next few years. As an integral part of our educational initiatives, we continue to involve several undergraduate students contributing to preparing their backgrounds for future research in the field of nanoscale manufacturing and electronics.

Benefit: These projects will have high impacts on several scientific fields, especially on spintronics both as physical properties point of view and also as nano-manufacturing point of view. They will also play an important role in collaboration with the leading industrial research laboratories e.g. for spintronics and could potentially initiate a joint project based on state-of-the-art MTJs and spin valves fabricated at such laboratories. I will be able to perform such activity at the University to initiate an international project on this topic. It will also help Ph.D. students and researchers to be able to perform research about these cutting-edge techniques and fields. We would also like to start a specialized program on spintronics at the University.

General criteria: Ethical issues will be respected and all data will be generally available after publication.

Citations

1. Akerman, J., *Toward a universal memory.* Science, 2005. **308**(5721): p. 508-510.
2. Slonczewski, J.C., *Current-driven excitation of magnetic multilayers.* Journal of Magnetism and Magnetic Materials, 1996. **159**(1-2): p. L1-L7.
3. Katine, J.A., et al., *Current-driven magnetization reversal and spin-wave excitations in Co/Cu/Co pillars.* Physical Review Letters, 2000. **84**(14): p. 3149-3152.
4. Sun, S.H. and C.B. Murray, *Synthesis of monodisperse cobalt nanocrystals and their assembly into magnetic superlattices (invited).* Journal of Applied Physics, 1999. **85**(8): p. 4325-4330.
5. Hergt, R., et al., *Physical limits of hyperthermia using magnetite fine particles.* Ieee Transactions on Magnetics, 1998. **34**(5): p. 3745-3754.
6. Colfen, H. and S. Mann, *Higher-order organization by mesoscale self-assembly and transformation of hybrid nanostructures.* Angew Chem Int Ed Engl, 2003. **42**(21): p. 2350-65.
7. JoseYacaman, M., et al., *Maya blue paint: An ancient nanostructured material.* Science, 1996. **273**(5272): p. 223-225.
8. Bentzon, M.D., et al., *ORDERED AGGREGATES OF ULTRAFINE IRON-OXIDE PARTICLES - SUPER CRYSTALS.* Philosophical Magazine B-Physics of Condensed Matter Statistical Mechanics Electronic Optical and Magnetic Properties, 1989. **60**(2): p. 169-178.
9. Sun, S., et al., *Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices.* Science, 2000. **287**(5460): p. 1989-92.
10. Zeng, H., et al., *Exchange-coupled nanocomposite magnets by nanoparticle self-assembly.* Nature, 2002. **420**(6914): p. 395-8.
11. Murray, C.B., C.R. Kagan, and M.G. Bawendi, *SELF-ORGANIZATION OF CDSE NANOCRYSTALLITES INTO 3-DIMENSIONAL QUANTUM-DOT SUPERLATTICES.* Science, 1995. **270**(5240): p. 1335-1338.

12. Disch, S., et al., *Shape induced symmetry in self-assembled mesocrystals of iron oxide nanocubes.* Nano Lett, 2011. **11**(4): p. 1651-6.
13. Park, J., et al., *Ultra-large-scale syntheses of monodisperse nanocrystals.* Nature Materials, 2004. **3**(12): p. 891-895.
14. Ahniyaz, A., Y. Sakamoto, and L. Bergstrom, *Magnetic field-induced assembly of oriented superlattices from maghemite nanocubes.* Proceedings of the National Academy of Sciences of the United States of America, 2007. **104**(45): p. 17570-17574.
15. Gleiter, H., *Our thoughts are ours, their ends none of our own: Are there ways to synthesize materials beyond the limitations of today?* Acta Materialia, 2008. **56**(19): p. 5875-5893.
16. Wolf, S.A., et al., *Spintronics: A spin-based electronics vision for the future.* Science, 2001. **294**(5546): p. 1488-1495.
17. Felser, C., G.H. Fecher, and B. Balke, *Spintronics: A challenge for materials science and solid-state chemistry.* Angewandte Chemie-International Edition, 2007. **46**(5): p. 668-699.