

Magnetic Properties of Low-Dimensional Systems II

New Developments

Proceedings of the Second Workshop,
San Luis Potosí, Mexico, May 23 – 26, 1989

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With 119 Figures

Springer-Verlag Berlin Heidelberg New York
London Paris Tokyo Hong Kong

XIV. Lattice Mismatched Magnetic Superlattices

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This is a brief review of our work on lattice mismatched magnetic superlattices. A number of physical phenomena at different length scales have been studied using lattice mismatched magnetic multilayered structures. These include thin film, interfacial, proximity, coupling, and superlattice effects in a variety of magnetic systems.

XIV.1. Introduction

Multilayered structures have been used for many years to study a large number of physical phenomena [XIV.1–XIV.3]. In general, phenomena to be studied can be categorized according to the length scale that determines the physics. “Long” length scale phenomena (above 100 Å) include low-temperature superconductivity, electric and magnetic dipolar coupling, whereas “short” length scale studies (below 100 Å) have concentrated on crystallization, magnetic coupling (RKKY, spiral magnetism), transport and epitaxial studies. Preparation and structural characterization have received considerable attention since in many cases the physical phenomena being studied require control of layer thicknesses at the atomic level.

The effects observed can be categorized in increasing order of complexity (according to the number of layers) as: thin film, dimensional, interfacial, proximity, coupling, and superlattice effects. **Thin film** effects can, in principle, be observed in single thin films; multilayers are collections of individual films. **Dimensional** effects occur because the thickness of the layers are smaller than a characteristic length in the problem. **Interfacial** effects are observable principally because of the presence of an interface between two dissimilar materials. **Proximity** effects occur due to the effect that one material has on another across an interface. **Coupling** effects can be studied in general if two like-layers are coupled across an unlike layer. The effects mentioned above, in principle, only require the study of a single, double, or triple layer. However, due to a number of technical reasons (contamination, signal size, etc.) it is more convenient to study these phenomena in multilayered structures, which does not require *in-situ* studies. Superlattice effects, on the other hand, intrinsically rely on the periodic nature of a superlattice and therefore cannot be observed in a few layers. A variety of superlattice effects have been predicted, including the observation of phonon folding, changes in the optical properties due to electric

dipolar coupling, changes in the electronic density of states in low-temperature superconducting superlattices, nonlinear I-V characteristics in metal/metal superlattices and the development of collective magnon bands in magnetic/normal superlattices. To the best of my knowledge, only phonon folding in GaAs/AlAs superlattices and collective magnon bands in Mo/Ni superlattices have been observed. I will describe here some of our work in this field, selecting representative examples from some of the categories described above.

XIV.2. Preparation and Characterization

Two principal methods of preparation have been used to manufacture multilayers: sputtering and thermal evaporation. Thermal evaporation in ultrahigh vacuum on heated substrates has been commonly designated as molecular beam epitaxy (MBE). The main advantage of sputtering is that it allows tuning the energy of particles at the substrate by changing sputtering pressure or target-substrate distance [XIV.4]. In addition, large volumes of sample can be prepared which can be used for low-sensitivity measurements or in applications requiring large areas, for instance X-ray optics. The main disadvantage of sputtering is the contamination produced by the sputtering gas and the fact that *in-situ* monitoring of growth is not possible. Thermal evaporation, especially in a UHV environment, on the other hand, permits *in-situ* monitoring of the growth and minimizes contamination. However, in general only small volume samples are produced and the maximum areas are limited. Both preparation methods are complementary. It is therefore interesting to compare structure and physical properties of samples produced by both methods.

XIV.3. Lattice Matching and Phase Diagram

It is commonly accepted that in order to improve the crystallographic quality of a superlattice, lattice matching is a necessary and sufficient condition. However, it is important to note that in many cases, systems that are lattice matched and have the same crystal structure, also form solid solutions in their thermodynamic phase diagram. In order to obtain atomically sharp interfaces, growth kinetics has to play an extremely important role to limit diffusion at the atomic level. In most case, however, the samples are grown at elevated enough temperatures, which makes interdiffusion likely. It is possible, therefore, that the thermodynamic phase diagram of the constituents plays a more important role than hitherto realized [XIV.5].

In order to avoid interdiffusion, our approach has been to concentrate on systems that do not exhibit any solid solutions in their thermodynamic phase diagram. As a consequence, the systems described here are lattice mismatched.

XIV.4. Structural Characterization

Structural characterization at the atomic level is an issue of major concern which has not been highlighted sufficiently. Theoretically, physical phenomena which occur at short length scales are strongly affected by a variety of structural defects which occur at the atomic level. These include interfacial roughness, interdiffusion, dislocations, stacking faults, etc. [XIV.6,XIV.7] To the best of my knowledge it is very difficult to ascertain, using one single technique, integrity of an interface at the atomic level. Many of the surface type probes such as Auger Electron Spectroscopy (AES), X-ray Photoelectron Spectroscopy (XPS), Low Energy Electron Diffraction (LEED), etc. are sensitive to electrons arriving from a finite escape depth from the samples. Scattering techniques, such as electron, X-ray or neutron diffraction, require extensive modelling which only recently is being addressed in detail [XIV.8]. Other structural probes, such as High Energy Electron Diffraction (HEED), although only sensitive to the first monolayer, have only been used to extract qualitative information and are not sensitive to chemical intermixing.

Clearly, only a comprehensive approach using a variety of techniques, together with quantitative modelling, will allow solving structural issues at the atomic level. I believe that in the near future more and more effort will be dedicated to issues related to structure at the atomic level.

It should be pointed out that a number of physical phenomena can be studied at large-length scale where structural defects at the atomic scale do not play a major role [XIV.9].

XIV.5. Magnetic Properties

The magnetic properties of lattice mismatched metallic superlattices exhibit a variety of interesting phenomena at short and long scales [XIV.9,XIV.10]. In general, the phenomena at short scales may be caused by unusual interfacial physics. However, the possibility of interfacial structure affecting the results has not been uniquely ruled out. These effects include the decrease in magnetization [XIV.11] and changes in first-order anisotropy in short wavelength Mo/Ni superlattices [XIV.12]. An interesting phenomenon at long scales (due to dipolar coupling) is related to the development of magnon bands in Mo/Ni superlattices [XIV.13].

a) Thin-film and interfacial effects

The saturation magnetization of Mo/Ni superlattices show systematic trends which are characteristic of thin-film [XIV.11] effects. Fig. XIV.1 shows the low-temperature saturation magnetization of Mo/Ni superlattices as a function of Ni thickness for three series of samples. Generally all the data fall close to a universal curve with the magnetization decreasing with Ni thickness. It is interesting

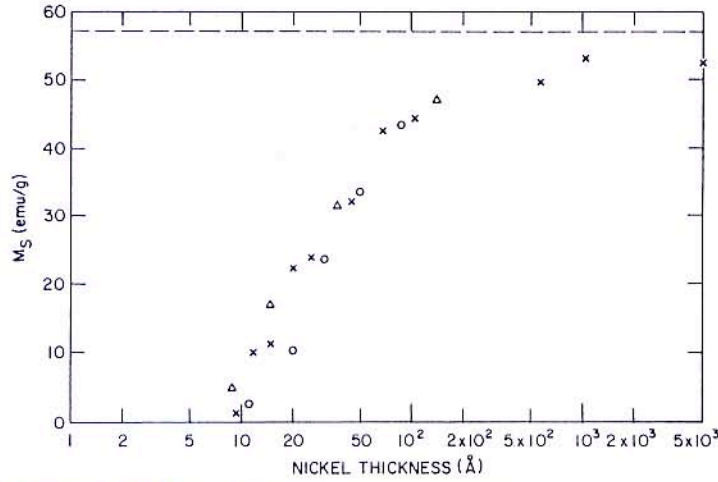


Figure XIV.1. Saturation magnetization as a function of nickel thickness for □, $D_{Ni} = 3D_{Mo}$; ×, $D_{Ni} = D_{Mo}$; ○, $D_{Mo} = 3D_{Ni}$.

to note that the curves with thinner Mo have a systematically higher saturation magnetization [XIV.9]. This type of behavior is typical of thin Ni films and is thought to arise from the fact that Ni atoms on the interfaces have fewer Ni nearest neighbors than the ones in the bulk. As a consequence, the (presumably) nonmagnetic interfacial Ni atoms become progressively more important in determining the *average* magnetization with decreasing layer thickness. The enhancement of the magnetization for thinner Mo layers could be due to a variety of effects; percolation ("shorts across the molybdenum"), or some form of magnetic coupling (RKKY, exchange, etc.) across the nonmagnetic molybdenum. This enhancement points out the need for clear-cut structural studies capable of establishing the perfection of the intervening nonmagnetic Mo layers. The X-ray diffraction data in this system indicates the presence of 1-2 atomic-planes roughness at an interface. Therefore, it is thought that the coupling effects arise because of percolation and not because of some more exotic coupling across a normal metal.

One interesting magnetic phenomenon at short scale is observed in the interfacial anisotropy [XIV.12]. Fig. XIV.2 shows a graph of the first-order anisotropy ($H_a^{(1)}$) as a function of Ni thickness measured by two different methods: DC magnetization and ferromagnetic resonance (FMR). To extract the first-order anisotropy from the DC magnetization, a fit to first- and second-order anisotropy was made, as shown in the inset to Fig. XIV.2. The first order anisotropy is in good agreement at large Ni thicknesses. However, for small thicknesses, there is a serious disagreement between the two types of measurements. This disagreement has been shown to scale inversely with the Ni thickness and therefore it is thought to arise from a surface contribution. At

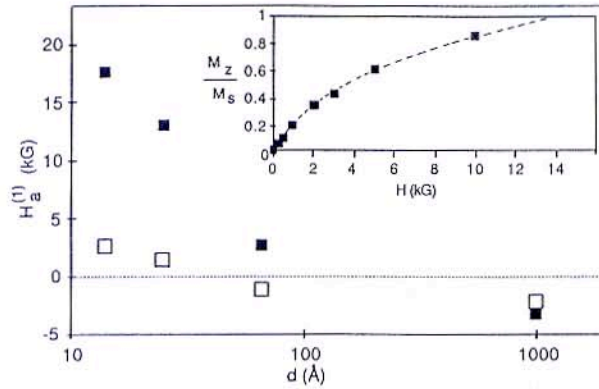


Figure XIV.2. Low-temperature, first-order anisotropy vs Ni-layer thickness for FMR (solid squares) and DC magnetization (open squares). The dotted line marks the transition from planar to perpendicular H_a . Inset: DC magnetization of Mo(25 Å)/Ni(25 Å) sample, compared to higher-order anisotropy model (dashed line).

this stage we should stress that irrespective of the details of the structure, the two types of measurements should give the same results. At present, the origin of this discrepancy has not been clarified. It may arise from an incomplete understanding of the measurements or maybe due to an enhanced anisotropy sensed and/or perhaps caused by the FMR experiment.

b) Superlattice effect

Superlattice effects rely on the existence of an additional periodicity imposed on the lattice by the superstructure. These types of effects cannot be observed even in principle in a few layers and require the additional superlattice periodicity.

The type of superlattice effects described here rely on long-range dipolar coupling. For this type of effects, structural perfection at atomic length scales is not crucial. The results of theoretical calculations [XIV.14,XIV.15] are schematically shown in Fig. XIV.3, where the frequency of magnon modes (ν) is plotted as a function of normal metal thickness (t_{normal}). An isolated thin film exhibits one “surface” mode whereas in the bulk material two modes are present, a surface and a bulk modes. In the transition region, a band of magnons is present. Theoretical calculations show that the coupling of light to the magnons has a higher density of states at the bottom of the band. The arrows show three series of Mo/Ni superlattice samples for which the magnon spectrum was measured, using Brillouin scattering techniques [XIV.13].

Fig. XIV.4 shows the frequency of the magnons for representative samples from the three series, together with fits to the theoretical models. The saturation magnetization extracted from these measurements are within 15% of independent measurements using DC magnetization measurements (see Fig. XIV.1).

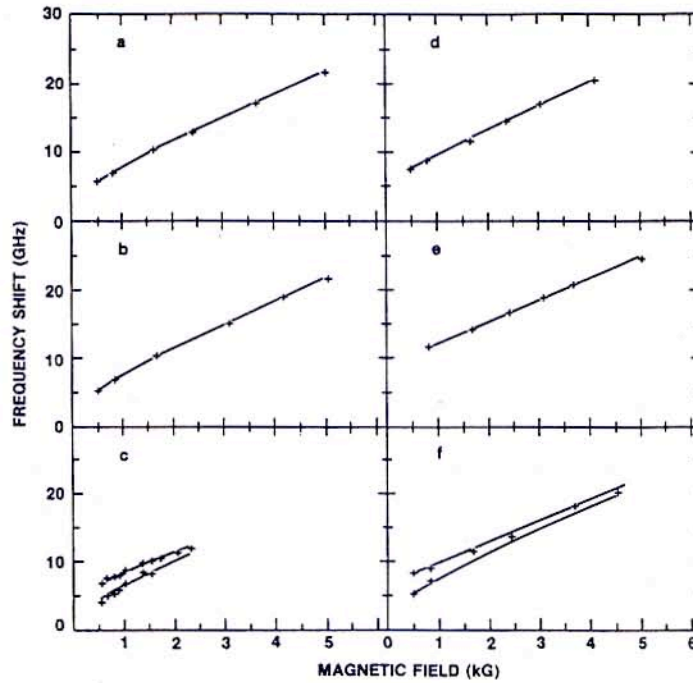
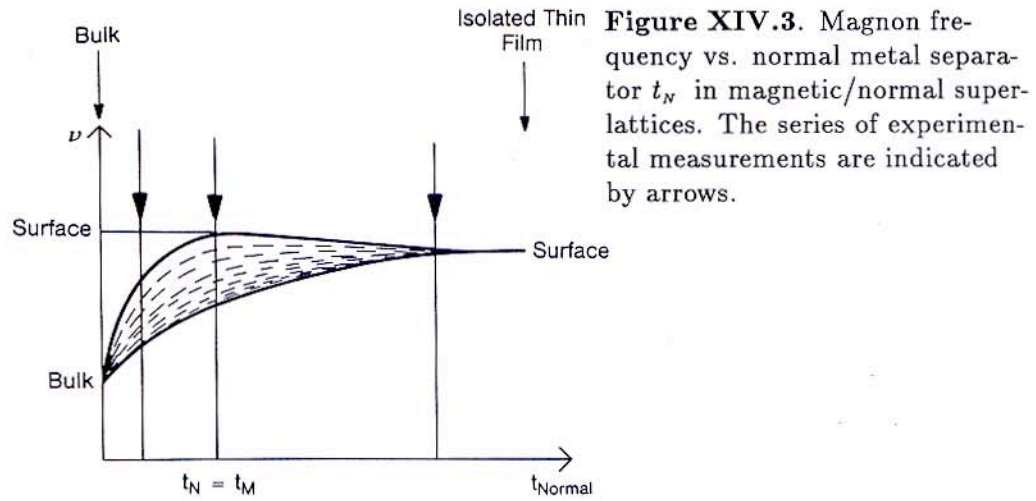


Figure XIV.4. Magnon frequency (crosses) for representative Mo/Ni superlattices vs. magnetic field together with theoretical fits (solid lines).

Measurements as a function of light scattering wavevector are also in quantitative agreement with the theoretical calculations. The excellent quantitative agreement between theoretical calculations and experimental measurement shows that the understanding of these phenomena is on firm footing.

XIV.6. Summary

Magnetic superlattices serve as ideal model systems to study physical phenomena in reduced dimensionality and to engineer novel properties. We have emphasized that phenomena which occur at short scales, below 100 Å require the preparation and characterization of samples with sharp, well segregated interfaces at atomic length scales. It is expected that future efforts will be dedicated to a thorough understanding of structure at the atomic scale. Several interesting applications were described which do not require atomic-scale structural perfection.

I thank my collaborators over several years and the Office of Naval Research for support in the initial stages of this work. Work supported by DOE grant #DE-FG03-87ER45332.

References

- XIV.1 *"Synthetic Modulated Structures"*, L. L. Chang and B. C. Giessen eds., Academic Press, Inc., Orlando (1985).
- XIV.2 *"Interfaces, Superlattices and Thin Films"*, J. D. Dow and I. K. Schuller eds., Materials Research Society Publishers, Vol. 77, Pittsburgh, PA (1987).
- XIV.3 *"Physics, Fabrication and Applications of Multilayered Structures"*, P. Dhez and C. Weisbuch eds., Plenum Publishing Co. (1988).
- XIV.4 K. E. Meyer, I. K. Schuller, and C. M. Falco, J. Appl. Phys. **52**, 5803 (1981).
- XIV.5 I. K. Schuller, Superlattices and Microstructures **4**, 521 (1988).
- XIV.6 See, for instance, D. B. McWhan in Ref. 1, pg. 43.
- XIV.7 See, for instance, D. B. McWhan in Ref. 2.
- XIV.8 See, for instance, J. P. Locquet, D. Neerincx, W. Sevenhans, Y. Bruynseraede, H. Homma, and I. K. Schuller in *"Multilayers; Synthesis, Properties and Non-Electronic Applications"*, T. W. Barbee Jr., F. Spaepen and L. Greer eds., Materials Research Society, vol. 103 (1988), pg. 217.
- XIV.9 See, for instance, I. K. Schuller and H. Homma, Materials Research Society Bulletin **XII**, 18 (1987).
- XIV.10 For a review, see I. K. Schuller in AIP Conf. Proc. **138**, 93 (1986).
- XIV.11 M. R. Khan, P. Roach, and I. K. Schuller, Thin Solid Films **122**, 183 (1985).
- XIV.12 M. J. Pechan and I. K. Schuller, Phys. Rev. Lett. **59**, 594 (1987).
- XIV.13 A. Kueny, M. Khan, I. K. Schuller, and M. Grimsditch, Phys. Rev. B **29**, 4915 (1984).
- XIV.14 P. Grünberg and K. Mika, Phys. Rev. B **27**, 2955 (1983).
- XIV.15 R. E. Camley, T. S. Rahman, and D. Mills, Phys. Rev. B **27**, 261 (1983).