MAGNETIC SUPERLATTICES

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ABSTRACT

Magnetic superlattices serve as model systems for the study of thin film, interfacial, proximity, coupling and superlattice phenomena. Due to these phenomena, the physical properties of magnetic superlattices can be tuned in a reproducible fashion by proper control of the preparation process.

Magnetic measurements in conjunction with detailed structural characterization provide a fruitful area of research, especially in understanding basic phenomena in magnetism. We describe here briefly a few experimental examples from our work which illustrate the possibilities magnetic superlattices offer for the study of basic phenomena in magnetism.

INTRODUCTION

The recent interest in the study of magnetic superlattices was motivated by the report of enhanced magnetization in Ni/Cu superlattices above the magnetization of pure Ni [1]. This report was coincidental with the development of novel preparation and characterization techniques for thin films, especially geared towards metallic systems [2-4]. As a consequence, great interest was devoted to the exploration of new magnetic superlattices, the study of magnetic phenomena at different length scales and the engineering of new magnetic properties into materials by careful control of preparation conditions. Among the large number of causes that could be invoked for the property modification of superlattices, changes in the electronic structure, proximity effects, and variations of thickness compared to a characteristic magnetic length (RKKY, dipolar and exchange) have received particular attention. In general, the properties of magnetic superlattices can be conveniently categorized according to the physics that gives rise to these properties. In increasing order of complexity (as far as number of layers required) these are: thin film, two dimensional, interfacial, proximity, coupling and superlattice effects. The recent literature in this field is quite extensive and beyond the scope of this brief review. For a comprehensive review, the reader is referred to several recent books on the subject [2-4]. To illustrate the type of effects present we will use examples from our own work.

PHYSICAL PHENOMENA

a) Thin Film and Two Dimensional Effects.

Thin film effects are due to the fact that a superlattice is made out of a collection of thin films. Although in principle, the observation of thin film effects do not require the incorporation into a superlattice, in practice, these present considerable technical advantages. Because a superlattice is made of a large collection of single layers, the total volume available for study is quite considerable so a number of studies can be performed which otherwise are not possible. In addition, in many cases single films require *in-situ* studies since surface oxidation presents a major problem when the sample is removed from the vacuum system. Since in superlattices only a small fraction of the sample is oxidized (typically 100 Å out of 10,000 Å) surface oxidation does not pose a problem.

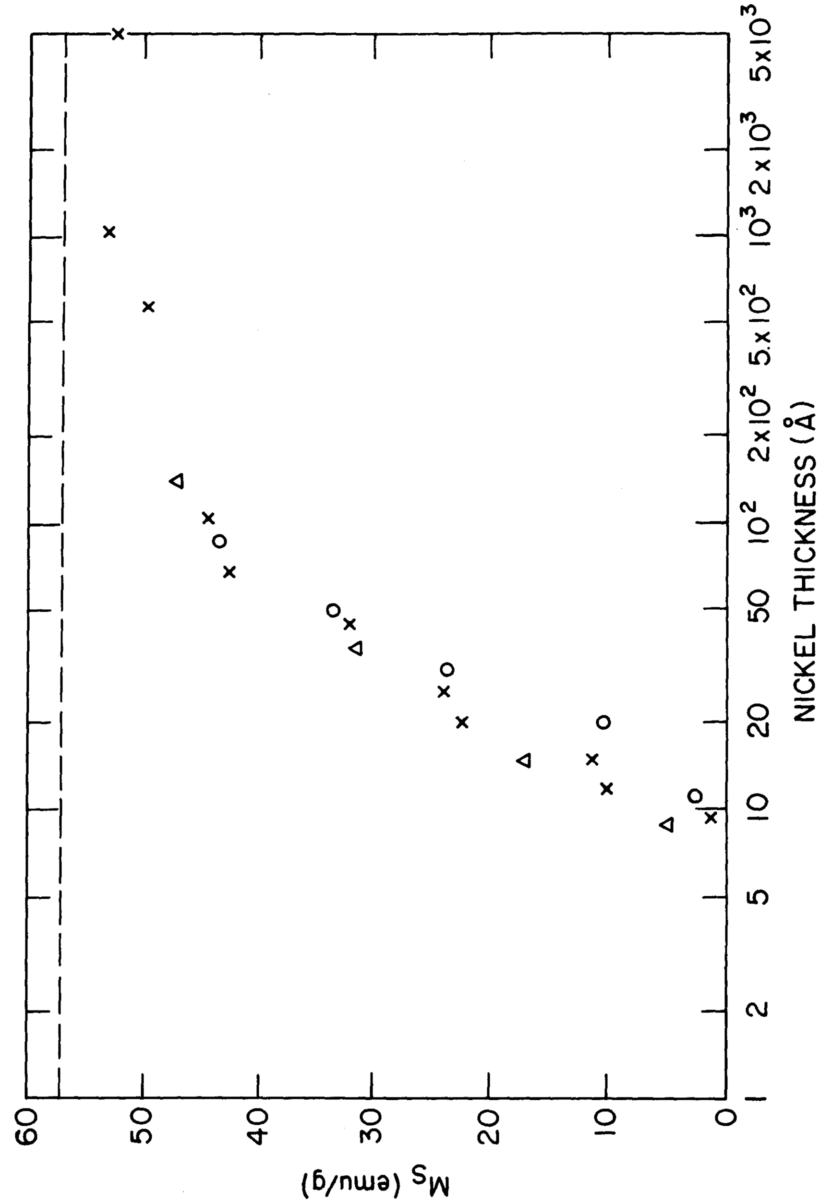

Fig. 1 Saturation magnetization (M_S) versus thickness in Mo/Ni superlattices. The dashed line indicates the saturation magnetization of bulk Ni.

An example of this type of effect is the decrease in magnetization and Curie temperature of Ni in Mo/Ni superlattices [5]. Fig. 1 shows the saturation magnetization (M_s) of Mo/Ni superlattices as a function of Ni thickness (d_{Ni}) at 5K. Close to d_{Ni} = 10 Å the saturation magnetization of the sample is below the detection limit, indicating that the sample is paramagnetic. A model assuming one to two dead layers of Ni at the interface between Mo and Ni explains quite well this curve. In addition, the Curie temperature (Fig. 2) shows a similar behavior. Note that these measurements were performed in multilayered samples after removal from the vacuum system, and the measurements were performed quite easily using a SQUID magnetometer.

The observation of dimensional effects in magnetic superlattices have been claimed by a number of groups [1,6,7]. In all these cases a remarkable linear temperature dependence of the saturation magnetization was observed close to monolayer superlattices. In order to uniquely identify whether this is a two-dimensional effect it is important to ascertain whatever roughness, pinholes, islands and other defects could give origin to this remarkable behavior.

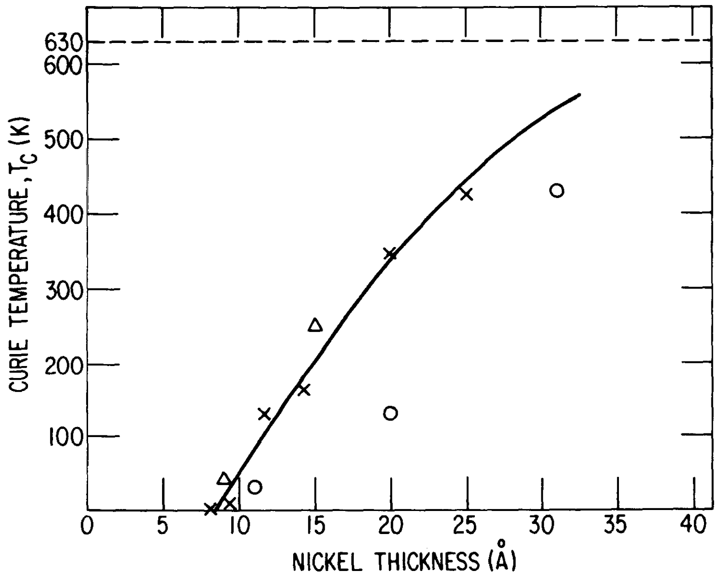

Fig. 2 Curie temperature extracted from Arrot plots for Mo/Ni superlattices. Note that Ni becomes non-magnetic close to a thickness of 10Å which corresponds to two dead layers at each interface.

b) Interfacial and Proximity Effects

The presence of an interface can cause a number of interesting effects either due to the presence of the interface (through the development of interfacial electronic states for instance) or because of proximity effects such as electron transfer.

One property which has received considerable attention in thin films is the behavior of the surface anisotropy. Very early [8] it was noticed that the anisotropy extracted from ferro magnetic resonance (FMR) and DC magnetization disagreed considerably. In addition, the perpendicular field dependence of the magnetization was not linear as expected in a thin film. In order to address some of these questions, we have performed an extensive study comparing FMR and DC magnetization in Mo/Ni superlattices [9]. The curvature in the DC magnetization (shown in the insert of Fig. 3) can be very well fitted for all fields assuming that second order anisotropy is important. Of course, this is the first and most natural explanation for the curvature. To compare the anisotropy from the parallel FMR and the parallel and perpendicular DC magnetization only first order anisotropies should be taken into account. The physical reason for this is that parallel FMR senses the anisotropy through small precesions of the magnetic moment from the parallel direction. The anisotropy measured using DC magnetization on the other hand, requires tipping the moment 90 degrees from the easy axis (parallel to the film) into the perpendicular direction to the film. This type of analysis brings into agreement the first order anisotropy $H_a^{(1)}$ for thin films as shown in Fig. 3. In equal layered superlattices, an increasing discrepancy with the number of interfaces is observed. Although the origin of this discrepancy has not been uniquely identified at the present time it is believed that this discrepancy arises from a surface anisotropy which is sensed by the high frequency FMR measurements [9].

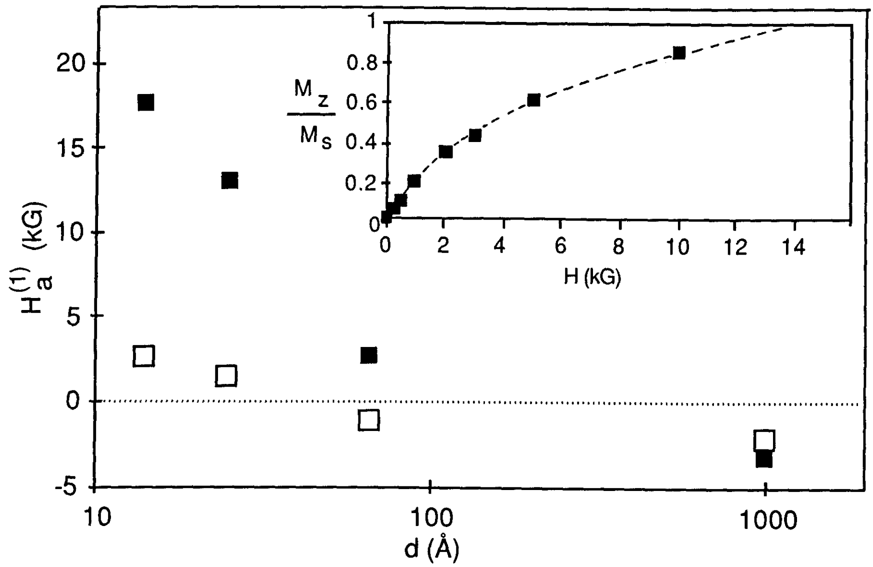

Fig. 3 The insert shows the magnetization in the perpendicular direction as a function of field. Dotted line is a fit assuming first and second order anisotropies. First order anisotropies obtained from DC magnetization (open squares) and FMR (closed square) measurements.

c) <u>Coupling and Superlattice Effects</u>

The coupling of magnetic layers across a normal metal has received attention for some time [10]. Recently, RKKY coupling in Gd/Y [11] and propagation of spiral magnetism in Dy/Y [12] superlattices have been claimed.

Since the coupling mechanisms investigated (RKKY and spiral magnetism) in these studies have all a decay length of the order of 10 Å, extreme control (at the atomic level) over the layer thickness, roughness, inter-diffusion, etc., has to be invoked. In addition, it is important to rule out the possibility of slight interdiffusion, pinholes, roughness, or other defects explaining the effects.

A coupling mechanism which occurs at relatively long length scales (larger than 100Å) is the magnetic dipolar coupling. In this case, the requirements on structural integrity is not that stringent. This coupling mechanism has allowed the observation of superlattice effects, i.e., effects which not only depend on coupling across non-magnetic layers, but also rely on the periodic nature of the superlattice.

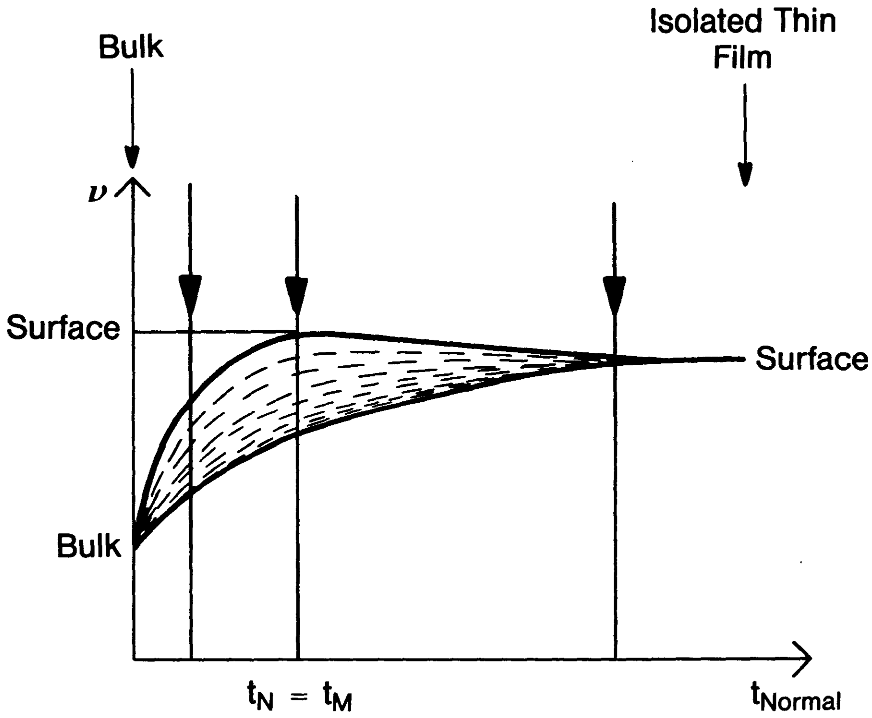

Fig. 4 Expected dependence of frequency versus thickness of normal metal.

Fig. 4 shows qualitatively the theoretical prediction for the frequency of magnons in a magnetic/normal superlattice as a function of normal metal thickness. For thick normal metal separator (i.e. isolated magnetic films) a single mode should be observed. When the normal layer thickness (t_N) becomes comparable to the magnetic layer thickness (t_M) one or two modes should appear depending on experimental broadening of the magnon lines. When the normal metal thickness becomes small, two distinct modes should be observed because the band of modes shown in the figure have a higher density of states at the bottom of the band. These effects have been calculated in detail [13,14] as a function of all parameters in the problem; t_N, t_M, magnetic field (H), scattering vector and saturation magnetization.

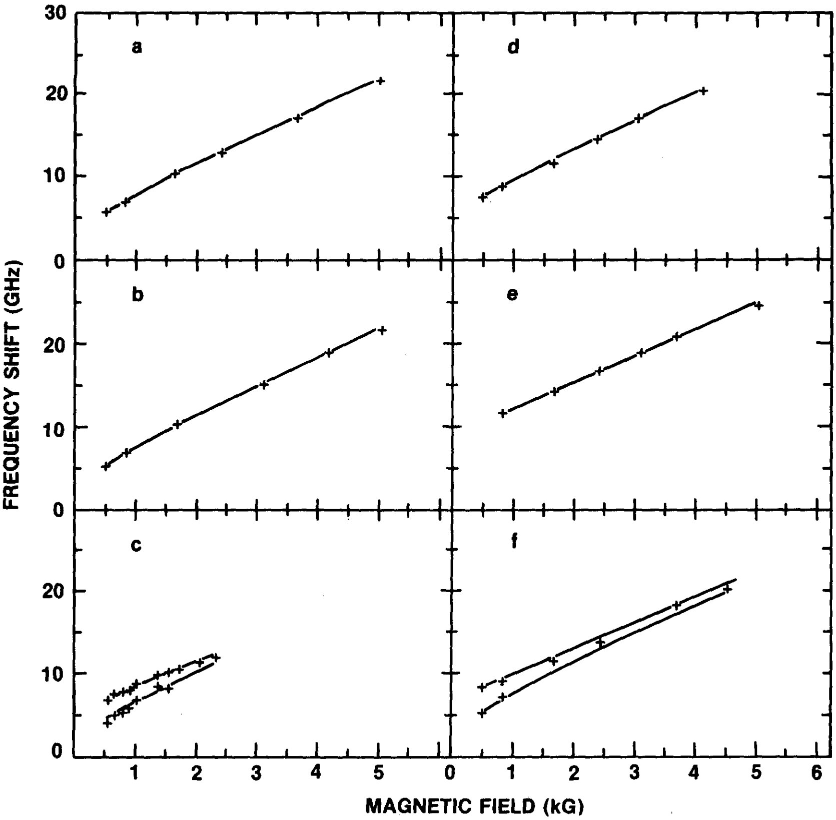

Fig. 5 Magnon frequency versus magnetic field for a series of Mo/Ni samples. The solid lines are theoretical fits as explained in the text.

The experiments [15,16] are in excellent, quantitative agreement with these theories without any adjustable parameters. For instance, the frequency shift as a function of H is shown in Figure 5, together with the theoretical prediction indicated by the solid lines. We should stress at this point, that the thickness at which superlattice effects due to dipolar coupling are observed are much larger than any imperfections possibly present in these materials.

CONCLUSIONS

In conclusion, magnetic superlattices have provided a very useful area of research. The phenomena that have been studied to date depend critically on the length scales which determine the physics. It is important to emphasize that the structural perfection needed for the observation of a particular effect varies considerably and therefore detailed structural characterization is imperative.

ACKNOWLEDGEMENTS

I thank my collaborators, M.R. Khan, M.J. Pechan, M. Grimsditch and A. Kueny for long years of interaction. I also thank my colleagues A.S.Arrot, M. Brodsky, G.P. Felcher, A.J. Freeman, E.M. Gyorgy, C.F. Majkrzak, D.B. McWhan, and G.P. Prinz for useful conversations. Work supported by DOE Grant #DE-FG03-87ER45332.

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