

BNL--36822
DE86 000208

CONF-850871--15

Neutron Diffraction Studies of Thin Film
Multilayer Structures

C. F. Majkrzak
Physics Department, Brookhaven National Laboratory
Upton, New York 11973

Abstract

The application of neutron diffraction methods to the study of the microscopic chemical and magnetic structures of thin film multilayers is reviewed. Multilayer diffraction phenomena are described in general and in particular for the case in which one of the materials of a bilayer is ferromagnetic and the neutron beam polarized. Recent neutron diffraction measurements performed on some interesting multilayer systems are discussed.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

1. INTRODUCTION

Thin film multilayers have become a subject of great scientific and technical interest ever since Esaki and Tsu [1] first proposed growing epitaxial multibilayers of two different semiconductor crystals. By imposing an artificial periodicity about an order of magnitude larger than the natural interatomic plane spacing, the conduction and valence bands of the bulk materials become subdivided into superlattice "minibands" where the superlattice band gap depends upon the bilayer thickness, composition and coherency strain at the interface [2,3]. Thus by choice of materials and modulation period, electrical and other properties can in principle be tailored.

The interest in synthesizing such novel structures is not, however, limited to semiconductor devices. Studies of multibilayer systems in which one of the constituents is ferromagnetic are contributing to our understanding of magnetism. Considerable theoretical efforts to describe the magnetic states of surfaces and interfaces have been made in recent years [4-6], although theories predicting such fundamental phenomena as the critical behavior at the surface or interface of a ferromagnet [7-9] remain largely untested. The interaction between magnetically ordered and superconducting states is another subject of current research [10] for which the choices of materials and modulation period that are possible with synthetically prepared superlattices is of value.

In principle the magnetization profile across the thickness of a thin ferromagnetic layer can be obtained from analysis of the diffraction of polarized neutrons by a multilayer. However, a correct

interpretation of this magnetization profile requires that the microscopic chemical structure of the multilayer be known, since the magnetic properties depend upon crystallographic orientation and interdiffusion and are affected by the coherency strains that can arise from lattice mismatch [6]. Furthermore, in certain cases the range of the magnetic interactions are of the same order as the thickness of the bilayer so that coupling between different ferromagnetic layers can occur. In fact, a possible crossover from three- to two-dimensional behavior in sufficiently thin and well separated magnetic layers can be investigated.

The role of neutron diffraction in the study of magnetic, superconducting and other multilayer systems is discussed in this paper. (The practical instrumental uses of multilayers as polarizers for neutrons and as monochromators for both neutrons and X-rays are described elsewhere [11-15].) The magnetism and superconductivity at a single surface can also be studied by neutron reflection techniques [16-18] and is the subject of another paper presented by G. Felcher at this Conference.

2. MULTILAYER DIFFRACTION

Consider the idealized case depicted in the lower part of Fig. 1 in which a multilayer is composed of M sets of N perfectly parallel, identical atomic planes of unit nuclear scattering length density for neutrons and with interplanar spacing d . Each set of planes is separated from adjacent sets by a vacuum space (or a material with a negligibly small coherent scattering length, e.g. vanadium) such that the superlattice or modulation wavelength is Δ . According to the

kinematical theory of diffraction (in which extinction is assumed to be negligible), the reflectivity R or ratio of scattered to incident beam intensity is given by

$$R(Q) = \frac{I_s}{I_0} = \left(\frac{4\pi}{Q}\right)^2 \left| \frac{\sin(NQd/2)}{\sin(Qd/2)} \right|^2 \cdot \left| \frac{\sin(MQ\Delta/2)}{\sin(Q\Delta/2)} \right|^2 \quad (1)$$

where $Q = |\vec{k}_f - \vec{k}_i| = 2|\vec{k}_i| \sin \theta$ is the magnitude of the scattering vector perpendicular to the planes, \vec{k}_f and \vec{k}_i are the final and incident wavevectors, respectively, and θ is the Bragg angle. The effects of static and dynamic fluctuations and absorption are neglected. The upper portion of Fig. 1 shows I_s plotted as a function of Q . The plot is divided into two regions, one at small Q or low angles, the other at higher values of Q centered about $Q = 2\pi/d$. For $M \geq 2$, diffraction maxima will in general occur at values of $Q = n 2\pi/\Delta$ where n is an integer. However, for certain values of N , d , and Δ , some orders may be forbidden, as illustrated in Fig. 1. In between adjacent principal diffraction peaks at small Q , there will appear $M-2$ subsidiary maxima. Note that in the particular case shown in Fig. 1, the forbidden principal diffraction peak at $n = 3$ is actually split into two subsidiary maxima while the central subsidiary maximum between $n = 1$ and $n = 2$ is itself split into two. The dashed line in Fig. 1 corresponds to the case for $M = 1$ but with intensity scaled to coincide with that of the principal maximum at $2\pi/\Delta$ for $M = 5$. At higher values of Q , diffraction maxima occur at integer multiples of $Q = 2\pi/d$ with satellites on either side at positions $Q = 2\pi/d \pm \ell 2\pi/\Delta$ (except at those integer ℓ forbidden for particular values of N , d and Δ). Between

these satellites, M-2 subsidiary maxima also appear. Once again the dashed curve corresponds to the case for $M = 1$ with intensity scaled to coincide with that for $M = 3$ at $2\pi/d$.

The quantity $\left| \sin(MQ\Delta/2)/\sin(Q\Delta/2) \right|^2$ in Eq. (1) has zeroes at $2\pi/\Delta \pm 2\pi/M\Delta$ for $M \geq 2$. For sufficiently large M the subsidiary maxima cannot be resolved in practice. Only the principal maxima, at $n 2\pi/\Delta$ and $2\pi/d$, and the satellites at $2\pi/d \pm k 2\pi/\Delta$ are distinguishable (as is observed, for example, in epitaxially grown GaAs/AlAs multilayers [19]). The Q-resolution of a spectrometer can, incidentally, be calibrated using multilayer samples with appropriate values of M .

In a more general case, the quantity $\left| \sin(NQd/2)/\sin(Qd/2) \right|^2$ in Eq.(1) can be replaced by the structure factor squared

$$|F|^2 = \left| \sum_{j=1}^N \rho_j e^{iQz_j} \right|^2 \quad (2)$$

where ρ_j is the two-dimensional scattering length density for the j th atomic plane and z_j its position from the origin of a unit cell of dimension Δ .

It is common in metallic thin films for textured growth to occur in which the film is composed of microcrystallites preferentially oriented with a particular crystallographic direction normal to the plane of the substrate but randomly oriented within the plane. Body-centered-cubic metals such as Fe and Nb prefer to grow with a $[110]$ close-packed direction normal to the substrate while face-centered-cubic metals such as Pd and Ni grow with the $[111]$ direction normal. However, this

alignment is not necessarily perfect and a distribution of angles between the preferred crystallographic direction and the substrate normal can exist. This mosaic structure does not directly affect the coherence length for diffraction from multilayers at small Q but at high Q the coherence between sets of N atomic planes in adjacent layers can be destroyed. The diffraction profile about $2\pi/d$ would then be similar to the dashed envelope in Fig. 1 that corresponds to a single layer of N planes. Of course the measured intensity would actually be an incoherent sum of the intensities contributed by each set of N planes. This is in fact what is believed to occur in Fe/Ge multilayers [20-22] in which the preferred Fe [110] directions have a mosaic spread of several degrees (the Ge layers are amorphous). Fig. 2 shows I_s at small Q for an Fe/Ge multilayer with $M = 11$ and $\Delta = 108 \text{ \AA}$ as obtained by X-ray diffraction. The inset shows unpolarized neutron diffraction data. The instrumental resolution is good enough to distinguish the $M-2$ subsidiary maxima between most of the principal low angle superlattice reflections at $Q = n 2\pi/\Delta$. Fig. 3 is another X-ray $\theta:2\theta$ scan of an Fe/Ge multilayer with $\Delta = 108 \text{ \AA}$ and $M = 609$ at higher Q about the Fe(110) reflection. The observed diffraction profile is what would be expected for $M = 1$ or a single set of N Fe(110) planes. The instrumental resolution of the diffractometer is 0.1° FWHM in 2θ and for the given Δ would be sufficient to distinguish the satellites that would occur at $2\pi/d \pm \ell 2\pi/\Delta$ if two or more sets of N planes were coherent. As it turns out, this particular diffraction profile is complicated by the presence of an interdiffusion layer of a crystalline

FeGe alloy with a d-spacing along \vec{Q} that is slightly different than that of pure Fe(110). This accounts for the pronounced asymmetry in the relative magnitude of the peaks on the high angle side of the principle maximum compared to those on the low angle side as discussed in references [22] and [23]. Note that the observation of a large number of higher-order superlattice reflections at low angles does not necessarily imply the existence of a sharp interface. On the other hand, no higher-order reflections will be present if the scattering density distribution is perfectly sinusoidal.

Multilayers composed of bilayers in which both constituents are crystalline and have preferred orientations in general exhibit more complicated diffraction patterns at high angles (see for example Refs. [24] and [25]). General discussions of multilayer diffraction effects are given by deFontaine [26], McWhan [27] and Segmüller and Blakeslee [28].

Up to this point extinction effects have not been considered. For an ideal multilayer consisting of perfectly parallel bilayers of uniform thickness, the first order superlattice reflection at $Q = 2\pi/\Delta$ can be affected by primary extinction even for a relatively small number of bilayers if Δ is large enough. However, simple theories of dynamical diffraction for perfect crystals cannot always be directly applied to multilayers in which some disorder is present. Consider the case of a multilayer in which any given layer has a constant thickness but where random differences in thickness exist from one layer to the next as a result of the variations in growth rate that occur during the deposition process. These thickness fluctuations have a cumulative effect and cause a successive broadening of higher order superlattice reflections that cannot be described by a static Debye-Waller factor. The proper

description is analogous to that for a one-dimensional system with no long range order [29]. However, even in this simple example it is not possible to use a statistical model if the number of bilayers is too small. On the other hand, if each layer is itself inhomogeneous in thickness (as a result of a stepped or roughened interface), then the number of actual layer thicknesses may be sufficiently large to constitute a statistical population, depending on the dimensions of the interface roughness and the coherence length of the radiation. Information about the nature of layer thickness variations can be obtained from measurements of the widths of the superlattice reflections and from the dependence of the reflectivity on the number of bilayers. Interface roughness can be studied by measuring the radiation scattered non-specularly about the incident beam direction set parallel and then perpendicular to the plane of the films. If the variations in the modulation period of the superlattice are large enough, then certain higher-order reflections will not even be observable in practice. Minimization of bilayer thickness fluctuations during the deposition process can therefore be crucial.

For diffraction at low Q , the scattering density profile of a bilayer can be treated as a continuum, whether the layers be epitaxial, textured, polycrystalline or amorphous. The structure factor can then be written as

$$F = \int_{-\Delta/2}^{\Delta/2} \rho(z) e^{iQz} dz \quad (3)$$

where $\rho(z)$ is now a

three-dimensional scattering density. It is sometimes necessary to account for mirror reflection and refraction effects at small Q (see for example Ref. [30]). The proper method of analysis is then analogous to that used in the solution of thin film optical interference problems and amounts to solving the Schrödinger equation for a plane wave incident upon and propagating through a layered but continuous medium [31]. Boundary conditions are imposed at each interface and the reflection and transmission coefficients subsequently evaluated. Random and systematic variations in bilayer thickness as well as absorption can be readily incorporated. This method is widely used in the design of multilayer monochromators and supermirrors [21, 32-34].

It is in principle possible to apply Fourier techniques to the problem of determining the scattering density profile of a multilayer. If, for example, a bilayer unit cell of length Δ is chosen so that $\rho(z)$ is an even function, then the scattering density can be written as a Fourier cosine series

$$\rho(z) = A_0 + 2 \sum_{j=1}^{\infty} A_j \cos \frac{2\pi jz}{\Delta} \quad (4)$$

where the A_j are the Fourier coefficients. It can be shown that the structure factor F_m evaluated at the low angle superlattice peak position given by $Q_m = m 2\pi/\Delta$ is proportional to the m th coefficient of the Fourier series expansion. The Fourier method can also be applied to the analysis of superlattice satellite intensities at high angles [19]. Nevertheless, Fourier analysis can be limited in practice by an insufficient number of observable higher-order reflections and the uncertainty in the signs of the coefficients.

It is then more practical to fit models of the scattering density

profile to the diffracted intensity data directly.

For non-magnetic multilayers, neutron diffraction measurements of the scattering density profile along the modulation direction are useful if the difference in the refractive indices of the two materials of the multilayer is small for X-rays but large for neutrons. However, it is the possibility of determining, with atomic resolution, the magnetization profile in ferromagnetic superlattices that is perhaps the most exciting application of neutron diffraction in the study of multilayer systems. This sensitivity to the ferromagnetic moment density distribution is enhanced if the neutron beam is polarized.

3. DIFFRACTION OF POLARIZED NEUTRONS BY A FERROMAGNETIC MULTILAYER

Consider a beam of neutrons incident upon a ferromagnetic multilayer in which the direction of the magnetization lies in the plane of the film. The scattering vector \vec{Q} is again normal to the plane of the film. If the incident neutron beam is polarized, then the structure factor at small Q is given by

$$F^{\pm} = \int_{-\Delta/2}^{\Delta/2} [\rho_N(z) \pm \rho_M(z)] e^{iQz} dz \quad (5)$$

where the + and - signs denote parallel and antiparallel neutron spin eigenstates and ρ_N and ρ_M are the nuclear and magnetic scattering densities respectively. The latter quantity is proportional to the atomic magnetic moment. Fourier analysis can again be applied as discussed in the preceding Section except that two expansions of the scattering density can be written, one corresponding to parallel and the other to antiparallel polarization of the incident beam. The magnetic scattering density profile $\rho_M(z)$ can then be obtained by combining the

two series assuming some model for the signs of the series coefficients. The nuclear scattering density $\rho_N(z)$ can be measured independently by aligning the magnetization along the scattering vector [35].

Alternatively, the measured integrated intensities \mathcal{I}_m^\pm defined by

$$\mathcal{I}_m^\pm \equiv \int_{\frac{1}{2} m 2\pi/\Delta}^{\frac{3}{2} m 2\pi/\Delta} I_s^\pm(Q) dQ \quad (6)$$

(and centered at $Q = m \frac{2\pi}{\Delta}$) or the corresponding "flipping" ratios

$$\mathcal{R}_m \equiv \frac{\mathcal{I}_m^+}{\mathcal{I}_m^-} \text{ can be directly compared with values calculated for a}$$

given model. The flipping ratios obtained in this way using the integrated intensities are in general different than the corresponding flipping ratios that result by dividing peak intensities at values of $Q = m 2\pi/\Delta$. It is therefore important to properly take into account the instrumental Q-resolution in measurements of peak intensities. In either case, however, the flipping ratios associated with certain reflection orders can change significantly for relatively small variations in magnetic moment at the interface [22].

In textured or epitaxial ferromagnetic multilayers, information about the magnetization profile can be extracted from polarized neutron diffraction data obtained at high angles about $Q = 2\pi/d$ as well [22, 36].

Figures 4 and 5 show polarized neutron data for an Fe/Ge multilayer at small and large values of Q respectively [22]. The Fe/Ge multilayer is composed of layers of Fe microcrystalites oriented with a [110] direction normal to the plane of the film (but randomly rotated within the plane) and of amorphous Ge layers as described in Section 2. In addition, there is an FeGe alloy region between adjacent Fe and Ge layers which is believed to account for the significant reduction in Fe moment that is deduced from an analysis of the diffraction data [22]. Unfortunately, if interdiffusion occurs it becomes difficult to separate the effects of alloying and reduced dimensionality on the magnetization at the interface even though the actual magnetization profile can be accurately determined from the diffraction measurements.

4. EXAMPLES OF ARTIFICIAL SUPERLATTICES STUDIED BY NEUTRON DIFFRACTION

Extensive theoretical calculations have been done on various epitaxial metallic overlayers, interfaces and superlattices which predict enhanced, reduced or even induced ferromagnetic moments (see for example, Refs. [4-6, 37]). Coherency strains or the lack thereof have profound effects on the magnetism. For example, it is presently believed that in bimetallic systems the absence of the negative pressures which arise from lattice parameter mismatches [38] diminishes the moment of a magnetic metal at the interface with a non-magnetic metal. A wealth of interesting and novel magnetic phenomena have been predicted to occur in synthetic layered structures.

Early neutron diffraction work on multilayer systems has been summarized in review articles by Endoh [39, 40]. In many cases, due to either a lack of detailed characterization of the chemical

microstructure of the films or an insufficient number of observable higher-order reflections, only qualitative or semiquantitative conclusions could be drawn from analysis of the neutron diffraction data alone. Most of the multilayer investigations involving neutron diffraction have been on ferromagnetic systems that were examined by a variety of other techniques including ferromagnetic resonance (FMR), Mössbauer Spectroscopy and X-ray diffraction (see, for example, Ref. [41]).

One ferromagnetic multilayer that has been studied in some detail is Ni/Cu. Jarlborg and Freeman [42] calculated the electronic and magnetic properties of a "coherent modulated structure" in which the basic repeat unit consists of three atomic layers each of Cu and Ni perpendicular to the [111] direction and predicted values of $0.50 \mu_B$ and $0.37 \mu_B$ for the central and interface Ni moments respectively. This prediction was in disagreement with the substantially enhanced magnetization deduced from FMR experiments [43] but consistent with average magnetization measurements [44, 45] and neutron diffraction measurements [46] which indicated a Ni moment that was reduced from that in pure bulk Ni but still greater than that in a disordered NiCu alloy. The existence of a large in-plane anisotropy was also established [44, 47] which explained the anomalous FMR results. Flevaris et al. [48] further found that for a Ni/Cu superlattice in which the bilayers consisted of 3 atomic planes of Ni and 6 atomic planes of Cu, the temperature dependence of the average magnetization was linear and, therefore, possibly indicative of two-dimensional magnetic behavior. However, in the multilayers studied by Gyorgy et al. [49], significant interdiffusion had occurred and the actual

chemical compositional modulation was found to be sinusoidal. Thus, as pointed out in a review of the work done on the Ni/Cu systems [50], a meaningful comparison of their experimental results with the energy band calculations of Jarlborg and Freeman [42] for a square-wave modulated structure cannot be made.

Interdiffusion is in fact the limiting factor in the study of the magnetic properties of many multilayer systems. In order to study magnetic critical behavior at the interface of a ferromagnet and another material, it is necessary to obtain neutron diffraction patterns at different temperatures through the Curie point (T_c). From this data the magnetization profile of the film can be deduced as a function of temperature. Unfortunately, for Fe, temperatures of several hundred °C must be sustained, thereby severely restricting the number of materials that can be investigated without alloy or compound formation and subsequent destruction of the superstructure itself [51, 22]. However, even for a ferromagnetic multilayer with T_c well below room temperature, appreciable interdiffusion can occur during the deposition process if elevated substrate temperatures are required for textured or epitaxial growth. For example, epitaxial EuS/SrS multilayers with a $T_c = 15K$ must be grown at substrate temperatures between 700 and 900°C [52] and an interface region consisting of $Eu_{0.5}Sr_{0.5}S$ forms which is expected to exhibit spin glass behavior [53]. Preliminary neutron scattering experiments are consistent with this picture [54]. More recently, epitaxial superlattices composed of M bilayers of N rare earth Gd (00 l) ($T_c =$ room temperature) and yttrium (00 l) atomic planes have

been successfully grown with relatively little interdiffusion [55]. Magnetic X-ray scattering has been used to study variations of the magnetic moment in these multilayers [56]. Polarized neutron diffraction measurements are also in progress and initial measurements have shown that the Gd moment can be measured in these thin films despite the enormous absorption cross section of Gd for neutrons [57].

In another interesting study, analysis of polarized neutron diffraction data on Mo/Ni superlattices has indicated a subtle effect where the ferromagnetic Ni moment depends more on its position relative to an average interface than to that of the individual microcrystallites or grains of which the film layers are composed [58].

Of related interest is the study of the interaction of ferromagnetism and superconductivity in multilayer systems. Once again neutron diffraction can be used to determine the magnetization profile of the ferromagnetic layers that are, in this case, in close proximity to a superconducting material. Fe/V and Ni/V multilayers have been studied by Mössbauer Spectroscopy, FMR and other techniques including neutron diffraction (see, for example, Refs. [59-62]). For Fe/V superlattices, only room temperature neutron diffraction data for the first-order superlattice reflections were obtained [59, 63]. Nevertheless, the results are in agreement with other measurements and with a model in which the moment of the interface Fe (110) layer alone is reduced from that of the bulk, although part of this reduction can be attributed to interdiffusion. Wong et al. [60] have reported that in Fe/V multilayers where the V layer thickness is of the order of the BCS coherence length and the Fe layer is just a few atomic planes thick, a

2D-3D crossover in the temperature dependence of the parallel upper critical field is observed, implying the coexistence of superconductivity and ferromagnetism. Further neutron scattering work is being done [64, 65]. Homma et al. [62] have reported anomalous behavior of the critical fields of Ni/V superlattices which is attributed to the competing interaction between the itinerant magnetism of the Ni layers and the superconductivity of the V layers. Polarized neutron diffraction measurements confirm that the Ni layers become nonferromagnetic in these superlattices for Ni layer thicknesses less than approximately 18 Å.

Antiferromagnetic and other more complicated structures can also be studied in multilayers by neutron diffraction over a wide range of scattering vectors. For example, the polycrystalline Fe (110) in-plane reflection in the Fe/Ge multilayers referred to above is readily observable even with a polarized beam [66].

The determination of the hydrogen density profile in hydrogenous multilayers is another possible application of neutron diffraction. For example, Nb/Pd [67, 68] and Nb/Ta [69] multilayers have been found to have greatly enhanced solubilities for hydrogen over that for the bulk materials. The average hydrogen density profiles can be indirectly inferred from atomic lattice spacing changes corresponding to shifts in the positions of Bragg reflections observed by X-ray diffraction. However, because the coherent scattering length of hydrogen for neutrons is negative and relatively large, the detailed hydrogen density profile along the modulation direction may in practice be obtained by analysis of the intensities of the superlattice reflections. Neutron diffraction

measurements on hydrogen loaded Si/SiO_x multilayers are also being performed in an effort to understand how the hydrogen density distribution affects various superlattice properties [70].

To conclude, neutron diffraction is in principle a powerful technique for studying the microscopic magnetic and chemical structures of synthetic superlattices. Polarized neutrons are particularly suited for determining the detailed magnetization profile along the modulation direction in ferromagnetic multilayers. Although actual diffraction measurements have so far been limited, the full potential of the method should be realized as progress is made toward the growth of ideal superlattices with minimal interdiffusion and variations in modulation period.

Acknowledgements

It is a pleasure to acknowledge the contributions of many colleagues at Brookhaven, particularly those of J. D. Axe, P. Böni, L. Passell and A. Saxena. Thanks are also due to Y. Endoh, G. Felcher, H. Homma, S. Malik, D. McWhan, A. C. Nunes, I. Schuller, S. Sinha and C. Vettier for many useful discussions. Research at Brookhaven was supported by the Division of Materials Sciences, U. S. Department of energy under contract No. DE-AC02-76CH00016.

REFERENCES

- [1] L. Esaki and R. Tsu, IBM Journal of Research and Development 14 (1970) 61.
- [2] G.H. Döhler, Sci. Am. 249 (1983) 144.
- [3] G. Osbourn, Phys. Rev. B27 (1983) 5126.
- [4] A.J. Freeman, J. Xu and T. Jarlborg, J. Magn. and Magn. Matls. 31-34 (1983) 909.
- [5] A.J. Freeman, H. Krakauer, S. Ohnishi, D. Wang, M. Weinert and E. Wimmer, J. Magn. and Magn. Matls. 38 (1983) 269.
- [6] A.J. Freeman, T. Jarlborg, H. Krakauer, S. Ohnishi, D. Wang, E. Wimmer and M. Weinert, Proc. of the Yamada Conf. VII, Muon Spin Rotation, Shimoda, 1983, Hyperfine Interactions 17-19 (1984) 413.
- [7] T. Wolfram, R.E. Dewames, W.F. Hall and P.W. Palmberg, Surf. Sci. 28 (1971) 45.
- [8] H.W. Diehl, J. Appl. Phys. 52 (1982) 7914.
- [9] K. Binder and D.P. Landau, Phys. Rev. Lett. 52 (1984) 318.
- [10] M.B. Maple and Ø. Fischer, Eds., Superconductivity in Ternary Compounds II (Springer-Verlag, New York, 1982).
- [11] C.F. Majkrzak, Applied Optics 23 (1984) 3524.
- [12] A.M. Saxena, and B.P. Shoenborn, Acta Cryst. A33 (1977) 805.
- [13] E. Spiller, in AIP Conf. Proc. 75, Edited by D.T. Atwood and B.L. Henke (1981) 124.
- [14] T.W. Barbee, Jr., in AIP Conf. Proc. 75, Edited by D.T. Atwood and B.L. Henke (1981) 131.
- [15] B. Vidal and P. Vincent, Applied Optics 23 (1984) 1794.
- [16] G.P. Felcher, R. Felici, R.T. Kampwirth and K.E. Gray, J. Appl. Phys. 57 (1985) 3789.

- [17] G.P. Felcher, R.T. Kampwirth, K.E. Gray and R. Felici, Phys. Rev. Lett. 52 (1984) 1539.
- [18] B. Farnoux, in Neutron Scattering in the 'Nineties (International Atomic Energy Agency, Vienna, 1985) 205.
- [19] R.M. Fleming, D.B. McWhan, A.C. Gossard, W. Wiegmann and R.A. Logan, J. Appl. Phys. 51 (1980) 357.
- [20] C.F. Majkrzak, J.D. Axe and P. Böni, Bull. Am. Phys. Soc. 29 (1984) 545.
- [21] C.F. Majkrzak and L. Passell, Acta Cryst. A41 (1985) 41.
- [22] C.F. Majkrzak, J.D. Axe and P. Böni, J. Appl. Phys. 57 (1985) 3657.
- [23] K.E. Meyer, G.P. Felcher, S.K. Sinha and I.K. Schuller, J. Appl. Phys. 52 (1981) 6608.
- [24] I.K. Schuller, Phys. Rev. Lett. 44 (1980) 1597.
- [25] W.P. Iowe, T.W. Barbee, Jr., T.H. Geballe and D.B. McWhan, Phys. Rev. B24 (1981) 6193.
- [26] D. deFontaine, in Local Atomic Arrangements Studied by X-ray Diffraction, Edited by J.B. Cohen and J.E. Hilliard (Gordon and Breach, New York, 1966) 51.
- [27] D.B. McWhan, in Synthetically Modulated Structures, Edited by L. Chang and B.C. Giessen (Academic Press, New York, 1985).
- [28] A. Segmüller and A.E. Blakeslee, J. Appl. Cryst. 6 (1973) 19.
- [29] J.D. Axe, in Physics of Structurally Disordered Solids, Edited by S.S. Mitra (Plenum, New York, 1976) 507.
- [30] A. Steyerl, K-A. Steinhauser, S.S. Malik and N. Achiwa, J. Phys. D18 (1985) 9.

- [31] P. Croce and B. Pardo, *Nouv. Rev. Opt. Appl.* 1 (1970) 229.
- [32] B. Hameiri, *Nucl. Instr. and Methods* 135 (1976) 299.
- [33] J. Schelten and K. Mika, *Nucl. Instr. and Methods* 160 (1979) 287.
- [34] S. Yamada, T. Ebisawa, N. Achiwa, T. Akiyoshi and S. Okamoto, *Annual Report Res. Reactor Inst. Kyoto Univ.* 11 (1978) 8.
- [35] M. Sato, K. Abe, Y. Endoh and J. Hayter, *J. Phys.* C13 (1980) 3563.
- [36] A.C. Nunes, C.F. Majkrzak and A.E. Berkowitz, *J. Magn. and Magn. Matls.* 39 (1983) 59.
- [37] C.L. Fu, A.J. Freeman and T. Oguchi, *Phys. Rev. Lett.* 54 (1985) 2700.
- [38] M. Brodsky and A.J. Freeman, *Phys. Rev. Lett.* 45 (1980) 133.
- [39] Y. Endoh, *J. de Physique* C7 (1982) 159.
- [40] Y. Endoh, N. Hosoiito and T. Shinjo, *J. Magn. and Magn. Matls.* 35 (1983) 93.
- [41] T. Shinjo, N. Hosoiito, K. Kawaguchi, T. Takada, Y. Endoh, Y. Ajiro and J.M. Friedt, *J. Phys. Soc. Japan* 52 (1983) 3154.
- [42] T. Jarlborg and A.J. Freeman, *Phys. Rev. Lett.* 45 (1980) 653.
- [43] B.J. Thaler, J.B. Ketterson and J.E. Hilliard, *Phys. Rev. Lett.* 41 (1978) 336.
- [44] E.M. Gyorgy, J.F. Dillon, Jr., D.B. McWhan, L.W. Rupp, Jr., R. Testardi and P.J. Flanders, *Phys. Rev. Lett.* 45 (1980) 57.
- [45] J.Q. Zheng, J.B. Ketterson, C.M. Falco and I.K. Schuller, *J. Appl. Phys.* 53 (1982) 3150.
- [46] G.P. Felcher, J.W. Cable, J.Q. Zheng, J.B. Ketterson and J.E. Hilliard, *J. Magn. and Magn. Matls.* 21 (1980) L198.

- [47] J.F. Dillon, Jr., E.M. Gyorgy, L.W. Rupp, I.Y. Yafet and L.R. Testardi, *J. Appl. Phys.* 52 (1981) 2256.
- [48] N.K. Flevaris, J.B. Ketterson and J.E. Hilliard, *J. Appl. Phys.* 53 (1982) 2439.
- [49] E.M. Gyorgy, D.B. McWhan, J.F. Dillon, Jr., L.R. Walker and J.V. Waszczak, *Phys. Rev.* B25 (1982) 6739.
- [50] E.M. Gyorgy, D.B. McWhan, J.F. Dillon, Jr., L.R. Walker, J.W. Waszczak, D.P. Musser and R.H. Willens, *J. Magn. and Magn. Matls.* 31-34 (1983) 915.
- [51] Y. Fujii, T. Ohnishi, T. Ishihara, Y. Yamada, K. Kawaguchi, N. Nakayama and T. Shinjo, *J. Phys. Soc. Japan*, to be published.
- [52] B. Saftic, N. Rasula, W. Zinn and J. Chevallier, *J. Magn. and Magn. Matls.* 28 (1982) 305.
- [53] W. Zinn, private communication.
- [54] C.F. Majkrzak and W. Zinn, unpublished data.
- [55] J. Kwo, E.M. Gyorgy, D.B. McWhan, M. Hong, F.J. DiSalvo, C. Vettier and J.E. Bower, to be published.
- [56] D.B. McWhan, C. Vettier, E.M. Gyorgy, J. Kwo, B. Buntschuh and B. Batterman, to be published.
- [57] C.F. Majkrzak, D.B. McWhan, C. Vettier and J. Kwo, work in progress.
- [58] G. Felcher, in *Dynamical Phenomena at Surfaces, Interfaces and Superlattices*, Edited by F. Nizzoli, K.H. Rieder and R.F. Willis (Springer-Verlag, New York, 1985) 316.
- [59] T. Shinjo, N. Hosoi, K. Kawaguchi, T. Takada and Y. Endoh, *J. de Physique* C5 (1984) 361.

- [60] H.K. Wong, B.Y. Jin, H.Q. Yang, J.E. Hilliard and J.B. Ketterson, to be published.
- [61] N.K. Jaggi, L.H. Schwartz, H.K. Wong and J.B. Ketterson, J. Magn. and Magn. Matls. to be published.
- [62] H. Homma, C.S.L. Chun, C.-G. Zheng and I.K. Schuller, to be published.
- [63] N. Hosoi, K. Kawaguchi, T. Shinjo, T. Takada and Y. Endoh, J. Phys. Soc. Japan 53 (1984) 2659.
- [64] G. Felcher, private communication.
- [65] Y. Endoh and C.F. Majkrzak, work in progress.
- [66] C.F. Majkrzak, J.D. Axe and P. Böni, unpublished data.
- [67] S. Moehlecke, C.F. Majkrzak and M. Strongin, Bull. Am. Phys. Soc. 28 (1983) 876.
- [68] S. Moehlecke, C.F. Majkrzak and M. Strongin, Phys. Rev. B31 (1985) 917.
- [69] P.F. Miceli, H. Zabel and J.E. Cunningham, Phys. Rev. Lett. 54 (1985) 917.
- [70] C.F. Majkrzak and B. Abeles, work in progress.

keywords

1. polarized neutrons
2. interface magnetism
3. thin film magnetization
4. superlattice
5. multilayer
6. diffraction

Figure Captions

- Fig. 1. Diffraction pattern at low and high Q for an idealized superlattice consisting of M sets of N atomic planes with periodicities Δ and d as shown schematically in the lower part of the figure. Details are described in the text.
- Fig. 2. X-ray diffraction pattern ($\Theta:2\Theta$ scan) for an Fe/Ge multilayer at low angles showing the principal maxima at integer multiples of $2\pi/\Delta$ along with the subsidiary maxima. The inset shows neutron data for the same sample about the first-order reflection, but with better instrumental resolution.
- Fig. 3. X-ray $\Theta:2\Theta$ scan of an Fe/Ge multilayer with $M = 609$ and $\Delta = 108 \text{ \AA}$ at high angles about $2\pi/d$ where $d = 2.03 \text{ \AA}$. The resolution of the diffractometer is 0.1° FWHM in 2Θ . (From Ref. [22].)
- Fig. 4. Polarized neutron diffraction data at low Q for an Fe/Ge multilayer. Seven diffraction peaks centered at values of $Q = m2\pi/\Delta$ are shown. The "ON" ("OFF") data points correspond to incident neutrons in the "+" ("-") spin eigenstate. The fact that the flipping ratio is not greater than unity for all orders implies a nonuniform magnetization in the ferromagnetic layer along the modulation direction. (From Ref. [22].)

Fig. 5 Polarized neutron diffraction data at high Q about $2\pi/d$, also for an Fe/Ge multilayer. To increase the signal, approximately 20 equivalent samples were superimposed. The difference in the widths for "+" ("ON") and "-" ("OFF") neutrons is indicative of a nonuniform magnetization across the thickness of the film. The instrumental resolution is $\approx 0.028 \text{ \AA}^{-1}$ FWHM. (From Ref. [22].)

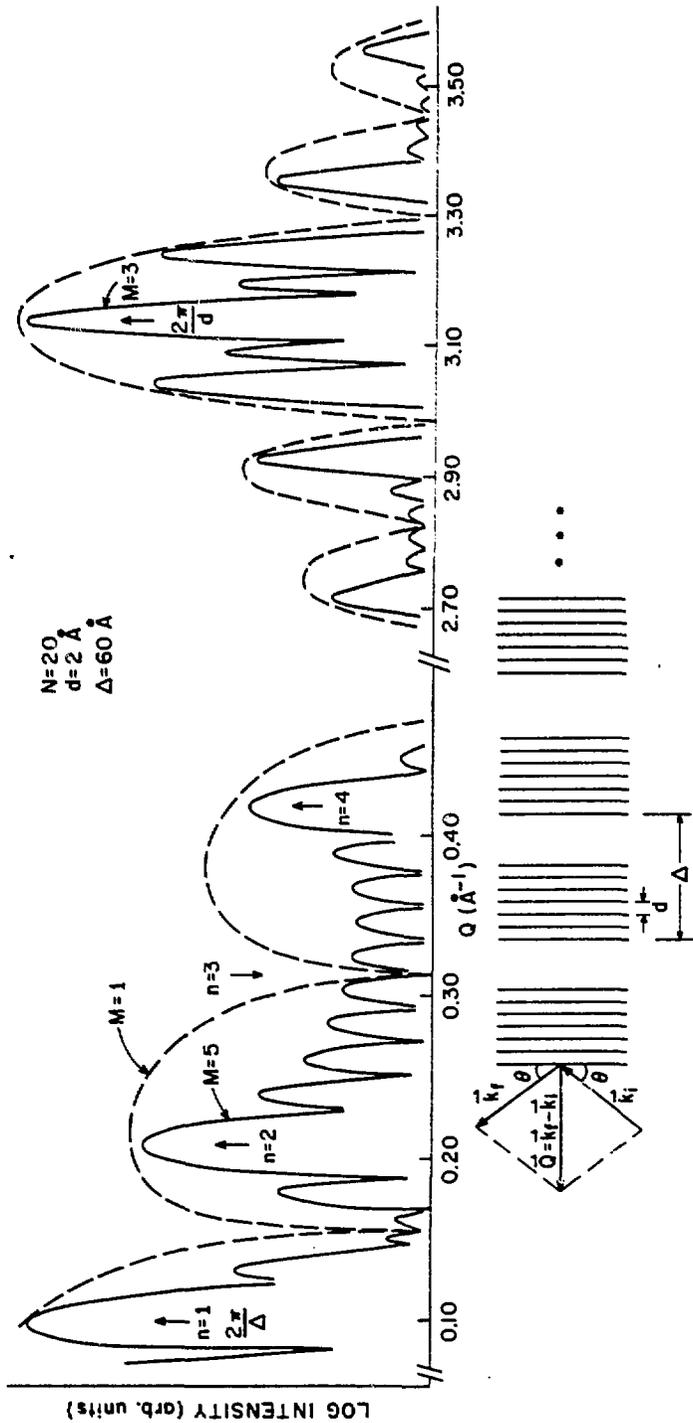


FIGURE 1

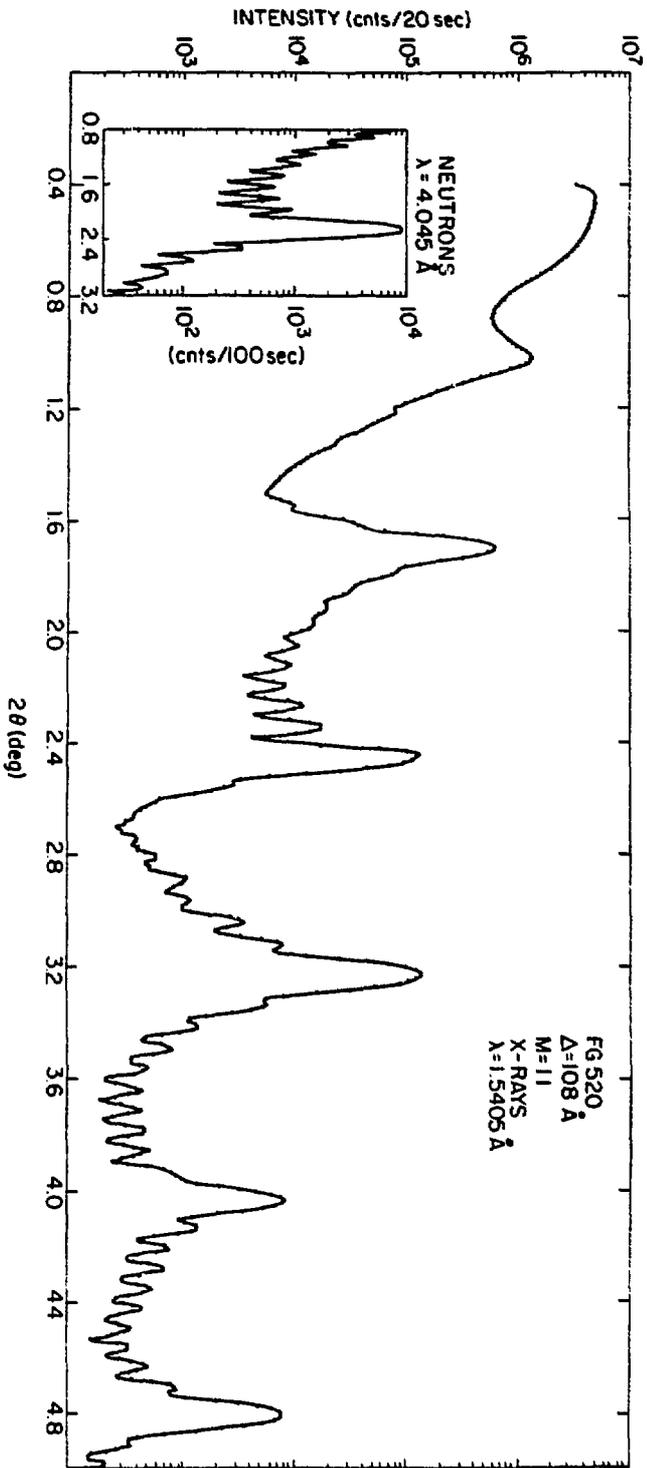


FIGURE 2

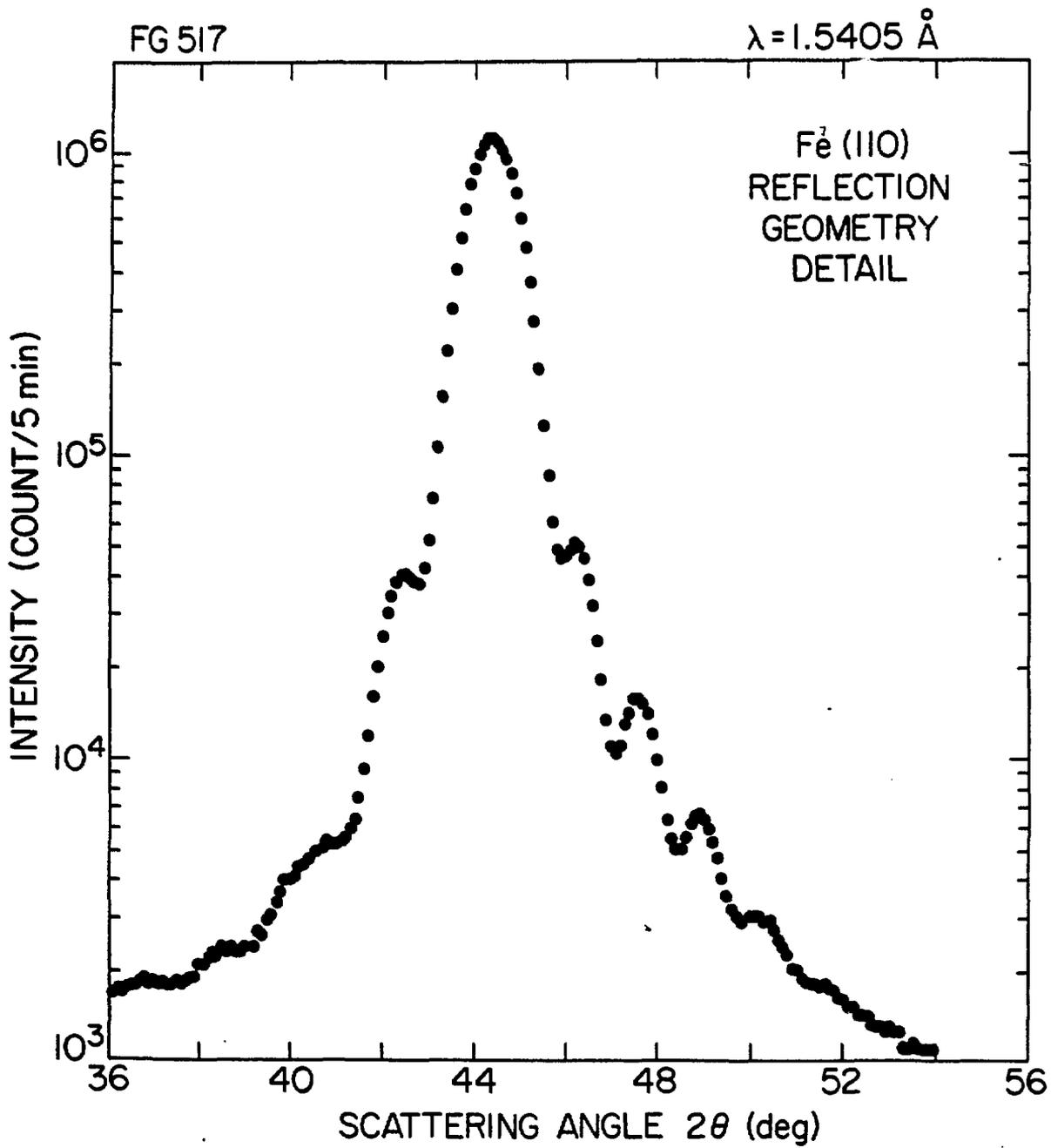


FIGURE 3

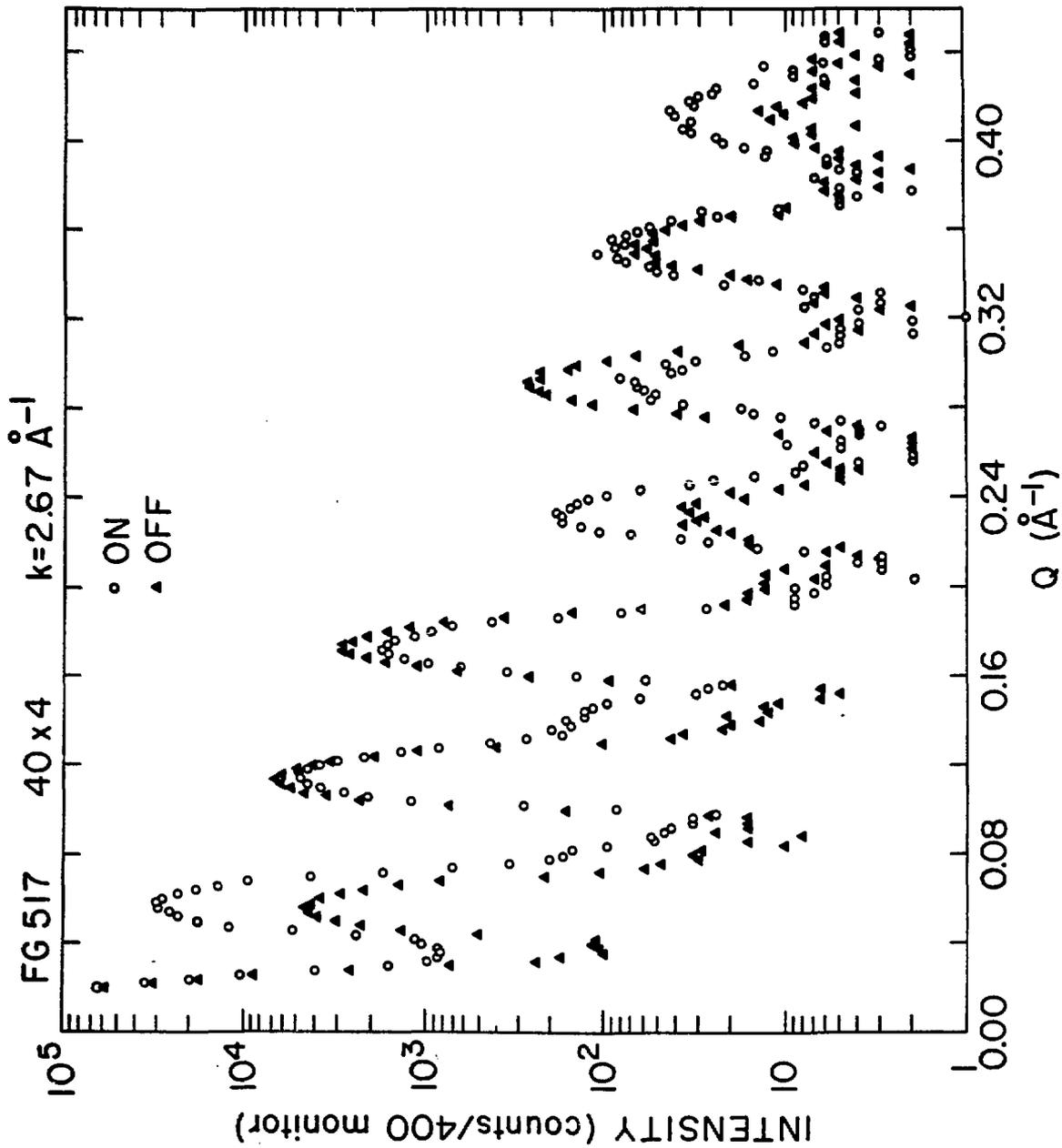


FIGURE 4

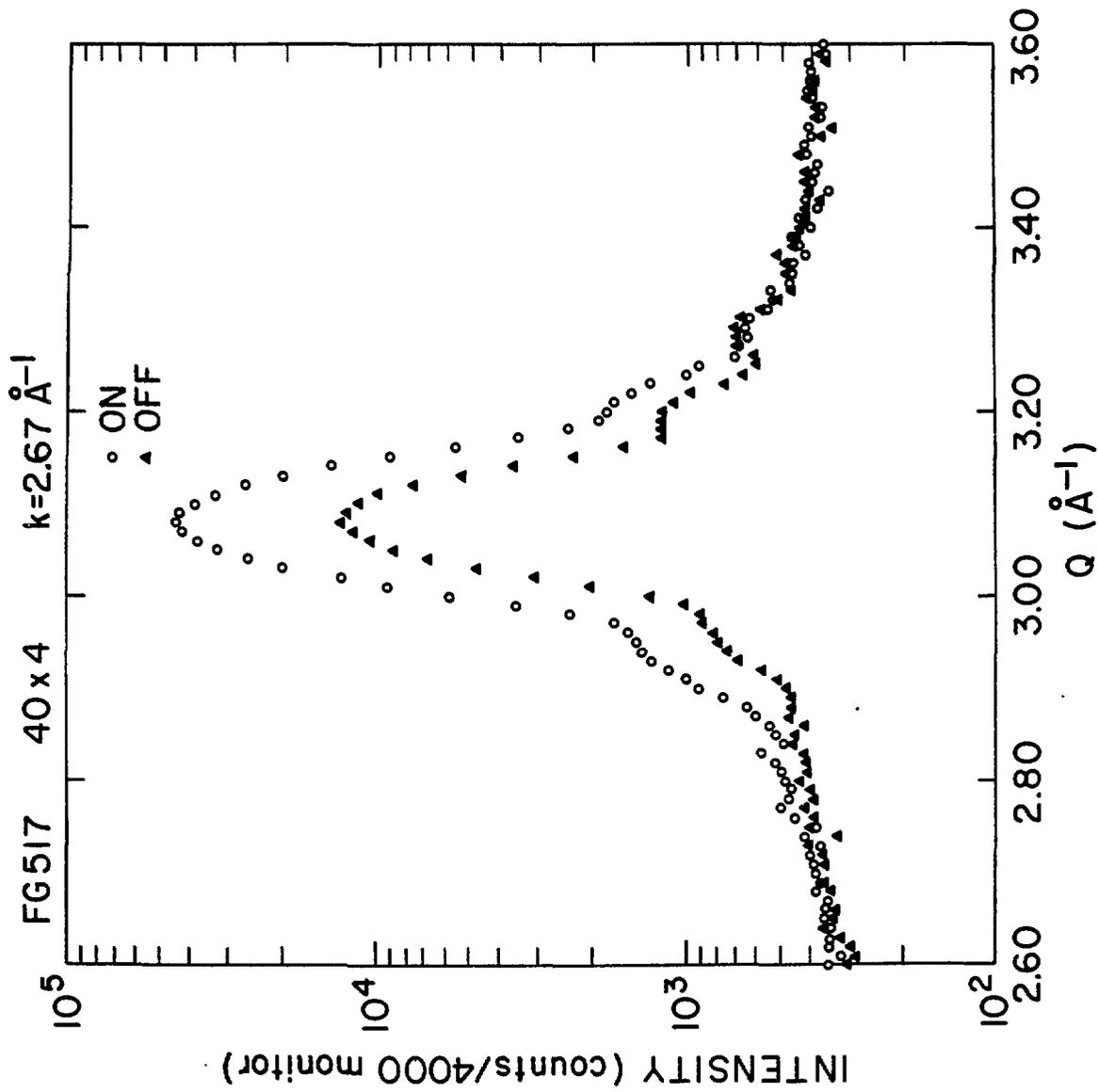


FIGURE 5