

The Interlayer Exchange Cu as a Function of Nonmagnetic On Giant Magnetoresistance Multilayers

Haji Shirinzadeh

Department semiconductors (Device Fabrication), Surface Physics and Thin Films
Material and Energy Research Center (MERC), Alvand Avenue, Tehran, Iran

Email: h_szadeh@merc.ac.ir

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ABSTRACT

This paper present a studies of magnetic multilayer structure and a key advantage of Molecular Beam Epitaxy preparation technique, and additional epitaxial over layers to study interlayer exchange coupling and the resulting reduction of growth induced defect are discussed.

Keywords: Thin films, CMR, magneto-resistance

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INTRODUCTION

In the 1960,s there were numerous breakthroughs in development of micro wave and optoelectronic devices. The need for high-performance and high-frequency devices is for in smaller dimensions and more stringent structure requirement. Many thin-film Technologies were used, as liquid phase epitaxy, chemical vapor deposition, sputtering and vacuum evaporation. The name Molecular Beam Epitaxy was first used in 1970. It distinguishes itself from the previous vacuum evaporation techniques with its ultra high vacuum environment much more precise control of the beam fluxes and deposition conditions. MBE is an epitaxial growth process involving the reaction of one or more thermal beam of atoms or molecules with a crystalline surface under ultrahigh-vacuum conditions. Films grown previously by vacuum evaporation did not have electrical and optical properties comparable to those grown by MBE. The knowledge of surface physics and the observation of surface structure variation resulting from the relations between the

rate of arrival of atoms (beam flux) and the substrate temperature allow considerable understanding of how to prepare high-quality thin films with the compilation of atomic layer upon atomic layer. The first high qualities of the MBE epitaxial magnetic super lattices layer were prepared in 1986, using MBE (Erwin et al., 1987; Kwo et al., 1988; Majkrzak, 1996). These rare-earth Gd/Y and DY/Y superlattices provided an elegant demonstration of indirect exchange coupling of $Gd(Dy)$ through the nonmagnetic Y layers via the $RKKY$ (Ruderman-Kittle-Kasuya-Yoshida) interaction. This interaction describes indirect exchange coupling between isolated spins mediated by spin-polarization of the conduction electrons of the metallic host. In the rare- earth super lattices the coupling occurs (at temperatures below $150K$) via a helical spin-density wave in the Y . The demonstration of $RKKY$ coupling in rare-earth super lattices led to interest in magnetic super lattices and sandwiches incorporating $3d$ transition metals with the prospect of discovering new room temperature magnetic

phenomena. MBE was used to prepare the artificially layered magnetic structures in which antiferromagnetic interlayer exchange coupling (Baibich et al., 1988; Binasch, Grünberg, Saurenbach, & Zinn, 1989), enhanced magnetoresistance (Prinz & Krebs, 1981), and GMR (Farrow, Parkin, & Speriosu, 1988) were discovered. The motivation for using MBE was the relative ease with which single-crystalline magnetic sandwiches and multilayers could be prepared by techniques developed earlier for epitaxial magnetic films (Etienne et al., 1988; Farrow, Parkin, Speriosu, Bezinge, & Segmuller, 1989) the discoveries of long-period interlayer exchange coupling and oscillatory GMR, the field widened with studies of many different combinations of materials. Parkin showed (S. S. Parkin, Hopster, Renard, Shinjo, & Zinn, 1992) that many spacer materials, in polycrystalline multilayers, had a similar long period ($\sim 10 - 12\text{\AA}$) for coupling and oscillatory GMR. Studies of single-crystalline, (001)-oriented sandwiches, using thickness wedges of the spacer, showed that both short and long periods were present for $Fe/Cr/Fe$ (Unguris, Celotta, & Pierce, 1993), $Fe/Ag/Fe$ (Demokritov, Wolf, Grünberg, & Zinn, 1991), and $Co/Cu/Co$ (Bruno & Chappert, 1991; Coehoorn, 1991; Johnson et al., 1992) showed that these periods are consistent with a theory based on RKKY coupling.

EXPERIMENTAL

All the thin film samples used in present study were prepared in an oil free Varian MBE – 360. S.P.a. Lein# SII/745. PICOTORR, 450 thin film deposition system. The preparation chamber 14" in diameter is of stainless steel (Figure 2) which meander type water cooling arrangement. Rough pumping of the chamber is done by *tubo pump* V450 units and final base pressure of 10^{-11} torr is obtained by 120l/s Starcell VacIon pump. The chamber has a Ferro fluid rotating feed through to accommodate a planetary substrate holder of stainless steel in which 4" dia can be loaded at one time different geometrical dimension of wafers. There are two electron guns of 10Kw each with a water cooled hearth of single 40_{CC} crucible and another four 30_{CC} crucibles. The thinness of the film is measured in-situ by three quartz crystal thickness monitor at different angle as coalse fitted with an Infion XTC process controller. The pressure in the chamber is measured by multiple pump control unit 929 Varian ionization gauge of Bayard-Alperd type. The substrates used were $6.0mm \times 6.0mm \times 0.5mm$ (001) oriented Si (111).

To enable the growth of high quality samples we have done org-omic chemical, for degrading oxide dissolution and forming a pre-oxide layer in ultrasonic bath before transferring in under ultra high vacuum in the MBE system. they were then out gassed at $800 - 900^{\circ}C$ for an hours. The further cleaning $10 - 15\text{\AA}$ monolayer's Oxygen contamination cleaning with an ion beam before deposition results in enhanced adhesion and reduced oxygen contamination. It could effect on lattice distortion. Pure elements (99.99%) of Co, Cu were used. The substrate temperature was varied two type's $300 - 500^{\circ}C$. At the rate $1\text{\AA}/s$ to thickness of 500\AA at ambient temperature $30^{\circ}C$. The

base pressure was 3×10^{-10} torr and 5×10^{-9} torr during deposition. To reduce the inter diffusion at the interfaces as Non equilibrium deposition. We exam crystal structure of the film surface were in-situ and throughout all the growth $30Kev$ reflection high energy electron diffraction (HREED). The crystal orientation was characterized by $x - Ray$ diffraction (XRD). The magnetic properties of all the samples were measured by (VSM) Magnetization curves were measured with applied field up to Films of three compositions were investigated; 250A, 130B, and 75C at %Co they have referred to as 250 Co/Cu 130 Co/Cu and 75 Co/Cu respectively. The x ray diffraction spectra of all sample showed a single phase fcc structure with broad lines and lattice spacing slightly shifted from pure Cu toward fcc Co . The sample was Vacuum annealed up to $750^{\circ}C$ for 45 min in preparation chamber. The crystal growth was carried out by molecular beam epitaxy system.

HISTORICAL INDUCTION OUR MOLECULAR BEAM EPITAXY (MBE) STATE

Molecular Beam Epitaxy the apparatus and techniques for molecular beam epitaxy growth have been basically slowest vacuum evaporation technique under ultrahigh-vacuum environment for the growth of epitaxial layers the source generally consist of from the constituent of thermal energy activated atomic or molecular beam. The growth is essentially kinetically limited, governed by the arrival rate and surface lifetimes of the impinging species, (Arthur, 1967; Arthur Jr, 1968; Goodenough, 1955; Gunther, 1958) though we note that equilibrium thermodynamics has been used to account for specific dopant incorporation (Grünberg, Schreiber, Pang, Brodsky, & Sowers, 1986). A significant advantage of MBE is its ability to incorporate UHV compatible surface analytical tools directly into the substrate preparation and growth chamber. Such tools assist in monitoring and confirming epitaxial growth as well as optimizing growth procedures and possibly trouble-shooting as well. UHV Techniques have more advanced considerably in recent years, to the extent that true UHV conditions (pressure of less than 10^{-12} Torr) are for the universal acceptance due to ultra clean & reproducible conditions. Because MBE is an inherently slow growth process it is possible to achieve extreme dimensional control over both major compositional variation and atomic doping in area epitaxy using simple mechanical masks. This chapter provides the experimental details of sample preparation monitoring of thin film growth and their analysis.

The thin film sample are prepared in-situ in a MBE system equipped with Electron Beam Epitaxy (EBE) made in a deposition system and are analyzed by two different UHV set ups with different techniques. Two important aspects of surface study of MBE growth under clean Ultrahigh-vacuum conditions to observe substrate surface and the quality surface during layer deposition. Furthermore it is heartening that the construction of phase diagram has been made possible from the knowledge gained on surface atomic structures using Reflection High-Energy Electron Diffraction (RHEED) ([24-29]. In (RHEED) an electron beam which

have energy in the range 5 – 10Kev is incident at a glancing angle of $1 - 2^{\circ}$ to the crystal surface which is set perpendicular to the molecular beam, allowing *RHEED* to be used during layer deposition. The technique provides a very sensitive yet simple diagnostic tool for observing changes in the structure of the surface layer as a function of growth parameters. It is possible to obtain information on surface structure, microstructure, and smoothness from *RHEED* pattern. To be deposited in an evaporator are directly related to the frequency of their reaction with the background gaseous species, systems with ever improving vacuum are necessary. The standard *MBE* system is shown schematically in figure 2. The system is pumped by combination of ion pumps and a titanium sublimation pump, the latter being enclosed in a liquid nitrogen shroud. The source ovens are resistively heated effusion cells made usually of material such as boron nitride. Shown in the figure are

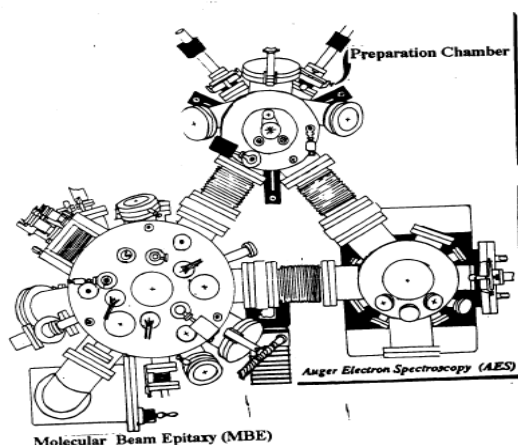


Fig 1. Schematic diagram of preparation chamber including electron beam evaporation effusion cell (Varian 981-3325)

The *MBE* system has two ovens, although as many as four for *K - Cell* and two *e - Gun* one single crucible 40mm and another 30mm × 4 crucibles, all six have been incorporated. In the growth of compound magnetic materials, as will be seen later, the materials contained in the ovens with different elements to be used as doping impurities. Individual thermocouples are embedded in the ovens. Shutters are provided for each source, and the entire assembly is surrounded by another liquid nitrogen shroud as shown. The substrate holder is located along the center line of the system, a few inches away from the openings of the ovens. In addition to sources and substrate, which are necessary parts in any evaporation system, monitoring, analyzing, and controlling equipment should be considered essential in a modified modern *MBE* system.

As shown in Fig.2 a spectral mass analyzer is located on axis at the side of the chamber, behind a liquid nitrogen shroud. It is capable of detecting the vaporizing as well as residual atoms or molecules and thus monitors both the thickness of the film and the environment under which the film is grown.

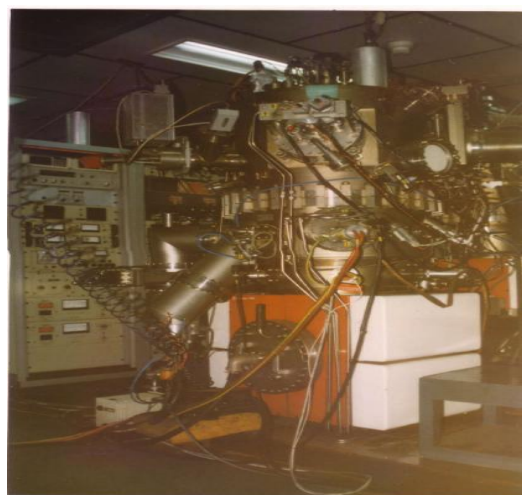


Fig 2. Modified modern *MBE* system

As shown in a spectral mass analyzer is located on axis at the side chamber, behind liquid nitrogen shrouded through an aperture in the screen. These patterns as discussed in many text and articles (Holloway, 1966), the smoothness, and in same case the reconstructed surfaces under various experimental conditions.

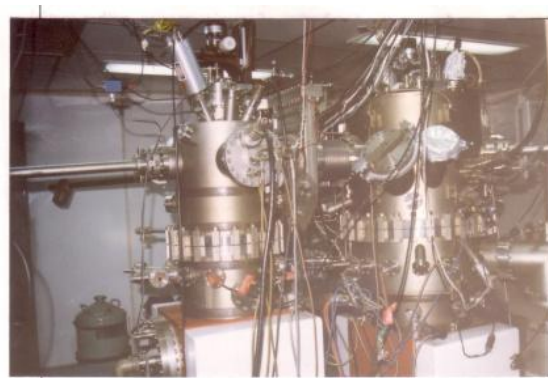


Fig 3. Photo standard *MBE* and *AES* system

The control unit could consist of simple analog controllers that correct the temperatures of source cells based on the thermocouple readings. It could also be a sophisticated, digital computing system when a high degree of precision in both composition and thickness is required. Based on the actual rate sensed by the mass analyzer, the computing system not only controls the cell temperatures but also commands the shutter operation. For in-situ examination of the growth, the apparatus further incorporates a scanning high-energy electron diffraction system, employing the small glancing angle, reflection mode of operation. The diffraction patterns can be viewed on a screen for qualitative information.

IN-SITUSTUDIES OF Co/Cu (111) MULTILAYES

The sandwiches Co/Cu multilayer's show (S. Parkin, Bhadra, & Roche, 1991) some of the largest values of *GMR* for any materials system. Qualitatively, the reason for this is that, near the Fermi energy, the band structures of Co and Cu

for majority carriers are similar, while the band structures for minority carriers are quite different (Nesbet, 1998). This leads to a large contrast in spin-dependent scattering of majority and minority carriers as they cross the Co/Cu interfaces. Because of the large GMR values and related technological interest in this system, GMR and interlayer coupling have been studied extensively in Co/Cu multilayer's and sandwiches using both magnetron sputtering and MBE as preparation techniques.

For sputtered polycrystalline multilayer's, it was found (S. Parkin et al., 1991) that for the most complete anti-ferromagnetic coupling between Co layers (corresponding to the largest GMR effect), it was necessary to use a Fe buffer layer to achieve flat, conformal Co and Cu layers. On the other hand, for structures prepared by MBE, it was found that while clear evidence existed for oscillatory exchange coupling through Cu in $Co/Cu(001)$ -oriented sandwiches (Cebollada et al., 1989; Giron et al., 1993; Heinrich et al., 1991), evidence for oscillatory interlayer exchange coupling in $Co/Cu(111)$ -oriented structures was contentious (Egelhoff Jr & Kief, 1992; Farrow et al., 1993).

In fact, lack of complete anti-ferromagnetic coupling at the appropriate spacer thicknesses was reported by many groups (Cebollada et al., 1989; Farrow et al., 1993; Schreyer et al., 1993). This lack of coupling was attributed (S. Parkin et al., 1991) to structural defects such as local ferromagnetic bridges, although no direct structural data were available at the time to support this suggestion. In situ studies of MBE-grown Co/Cu multilayer's and sandwiches were then carried out to determine the effect of growth conditions on interlayer exchange coupling and GMR. Farrow et al. (1993) prepared $Co/Cu(111)$ -wedged multilayer's in which the Cu layers were nearly linear wedges in thickness but the Co layers were of constant thickness. Comparison between MBE growth and sputtering of GMR and AF coupled structures As discussed above, the absence of oscillatory GMR and interlayer exchange coupling in MBE-grown $Co/Cu(111)$ multilayer's was correlated with growth-induced defects arising from twinned islanding of Co on $Cu(111)$ terraces. Polycrystalline, sputtered Co/Cu multilayers are likely to have a very small fraction of (111) terraces available during growth, and if their size is small enough, migration of ad atoms to surface steps precludes islanding. For this reason, the mechanism for ferromagnetic bridging, operative in MBE growth of $Co/Cu(111)$ is absent. This explains the clear observation of long-period, oscillatory GMR and interlayer coupling for these sputtered structures. However, it raises the question as to whether ferromagnetic bridging is present in epitaxial $Co/Cu(111)$ multilayers prepared by sputtering. In recent years it has been shown that growth of highly oriented and single-crystalline magnetic structures by sputtering is possible if epitaxial seed films are first grown onto single-crystal substrates. For example, by using seed-film/substrate combinations similar to those in MBE, highly oriented or single-crystalline magnetic metal sandwiches and multilayer's can be grown by sputtering (Farrow et al., 1993; Harp, Weller, Rabedeau, Farrow, & Toney, 1993; Mattson, Fullerton, Sowers, & Bader, 1995). The clearest picture to date of oscillatory interlayer coupling through $Cu(001)$ in

the $Co/Cu(001)$ system comes from the work of (Weber et al. 1996). They have shown that MBE growth of wedged, single-crystalline $Co/CuCo(100)$ trilayers on single-crystal $Cu(001)$ substrates, combined with spin-SEM (identical with SEMPA), provides a detailed picture of both long and short-period oscillatory interlayer exchange coupling. The measured long and short periods are in good agreement with theory. However, the relative amplitudes of the two types of oscillations changed dramatically when a different Cu substrate crystal was used. This was attributed to the influence of substrate on Cu spacer layer roughness, demonstrating how sensitive interlayer coupling is to growth conditions and interface roughness. Indeed, magnetic anisotropy is also sensitive to roughness on the atomic scale, for this material system (Weber et al., 1996). Monolayer periods of roughening and in-plane lattice spacing (Fassbender et al., 1995) have been detected using RHEED observations of $Co/Cu(001)$ growth in real time, demonstrating the value of in situ probes for investigating oscillations in magnetic anisotropy. This emphasizes an advantage of MBE over sputtering: The background pressure during magnetron sputtering precludes the use of electron beam probes such as RHEED and SEMPA during growth. Surface level saturation under a proper growth condition, through the number of surface level increase slightly, it saturates at several mono layer, (3a) shows the growth were island and holes are absorb on the terrace –and –step saturation and (3b) shows the morphology after several-layer growth islands (white) and holes (black) are coexisting steadily. Now the above results are compared with the growth of Si in case of Si growth on $Si(111)7x7$ reconstructed surface, it is reported that the island nucleation (Giron et al., 1993; Heinrich et al., 1991). In present case, the delayed nucleation takes place also, thus in both case surface reconstruction provokes the delayed nucleation (in different way) as result of step propagation growth mode. At a relatively high substrate temperature and a low growth rate of $0.01\text{\AA}/s$, the surface features at the beginning of growth in fig 3(a) are a circular dark line on the center, slightly declining to around outer.

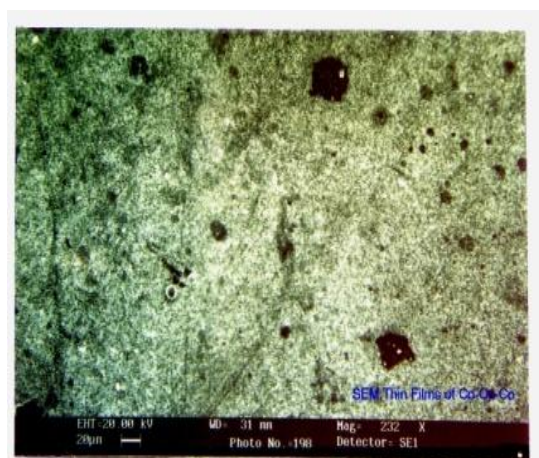
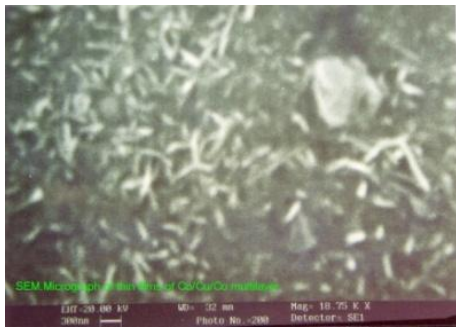
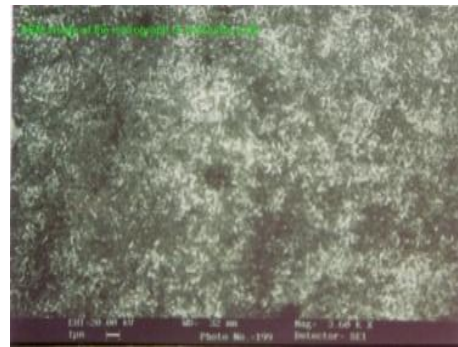
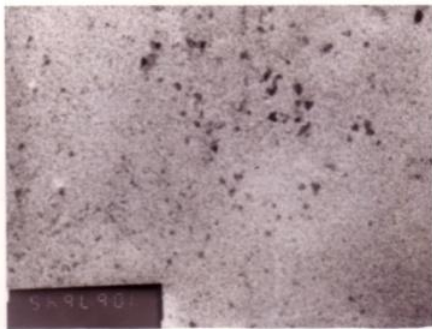


Fig 4. Photograph 4.SEM image of the micrograph of $Co/Cu/Co$ on Si

Fig 5. SEM thin film of $Co/Cu/Co$ Fig 6. SEM micrograph of thin films $Co/Cu/Co$ multilayerFig 7. SEM image of the micrograph of $Co/Cu/Co$ on SiFig 8. TEM micrograph of $Co/Cu/Co$

RESULT AND DISCUSSION

The contributions of MBE and sputtering to this field continue to be complementary. In situ probing of MBE-grown, epitaxial $Co/Cu/Cu$, $Co/Fe/Cr$, and other sandwiches using *RHEED* for precise spacer thickness determination, combined with the magnetic probes of spin-SEM (SEMPA) and the magneto-optical Kerr effect, are leading to a detailed picture of both short- and long-period oscillatory interlayer exchange coupling. Oscillations in several other magnetic properties (magnetic anisotropy, magneto-optical response) also show oscillations with interlayer thickness originating from intrinsic phenomena (Quantum-well states spin density wave oscillations) In some cases, extrinsic phenomena also play a role, as in the case of monolayer-period oscillations in magnetic anisotropy of $Co/Cu/Co$ (001) resulting from periodic changes in over layer roughness. For some materials systems, especially Co/Cu (111)-oriented sandwiches and multilayer's, the growth process can produce defects (local ferromagnetic bridges) which have a strong extrinsic influence on GMR and interlayer exchange coupling. These defects result from incomplete coalescence of twinned islands of Co and Cu and can be suppressed by growth in the presence of a surfactant (*Pb*) which eliminates twinning. On the other hand, in perm alloy/*Au*(111) super lattices, twinning is also present, but there is little evidence for ferromagnetic bridging. High-resolution electron microscopy studies suggest that this may be due to the tendency for twin boundaries in the perm alloy to terminate at the interface to the Au layers. The mechanism

for this behavior is not yet clear, and further work is needed to examine growth mechanisms and step edge barriers to ad atom migration. Similarly, in the Co/Cu (001) system, oscillatory interlayer exchange coupling is sensitive to the growth process in that the relative amplitudes of short- and long-period interlayer exchange coupling are influenced by initial roughness of the substrate and of the Cu/Co interfaces. Here also, STM studies of the development of interface roughness as a function of growth conditions, combined with in situ probes of the coupling, are needed.

CONCLUSIONS

A major role of MBE in connection with GMR and interlayer exchange coupling is in developing a more complete understanding of these phenomena and in clarifying the influence of growth conditions on them. SEMPA-wedge experiments and micro structural studies of MBE-grown perm alloy/*Permally*/*Au*(111) multilayer's exemplify this approach. On the other hand, sputtering (by dc magnetron or ion-beam methods) is the deposition method of choice for magnetic storage devices (for example, spin-valve GMR read heads) because of its high throughput. Sputtering can be used to produce magnetic sandwiches and multilayer's with record values of GMR. Its use has facilitated major contributions to our understanding of GMR and interlayer exchange coupling as well as an expansion of the range of materials systems exhibiting these phenomena. MBE growth and sputtering can therefore be viewed as complementary techniques.

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REFERENCES

- Arthur, J. (1967). Vapor pressures and phase equilibria in the Ga - As system. *Journal of Physics and Chemistry of Solids*, 28(11), 2257-2267.
- Arthur Jr, J. (1968). Interaction of Ga and As₂ molecular beams with GaAs surfaces. *Journal of Applied Physics*, 39(8), 4032-4034.
- Baibich, M. N., Broto, J., Fert, A., Van Dau, F. N., Petroff, F., Etienne, P., . . . Chazelas, J. (1988). Giant magnetoresistance of (001) Fe/(001) Cr magnetic superlattices. *Physical Review Letters*, 61(21), 2472.
- Binasch, G., Grünberg, P., Saurenbach, F., & Zinn, W. (1989). Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange. *Physical Review B*, 39(7), 4828.
- Bruno, P., & Chappert, C. (1991). Oscillatory coupling between ferromagnetic layers separated by a nonmagnetic metal spacer. *Physical Review Letters*, 67(12), 1602.
- Cebollada, A., Martinez, J., Gallego, J., de Miguel, J., Miranda, R., Ferrer, S., . . . Rebouillat, J. (1989). Antiferromagnetic ordering in Co-Cu single-crystal superlattices. *Physical Review B*, 39(13), 9726.
- Coehoorn, R. (1991). Period of oscillatory exchange interactions in Co/Cu and Fe/Cu multilayer systems. *Physical Review B*, 44(17), 9331.
- Demokritov, S., Wolf, J., Grünberg, P., & Zinn, W. (1991). *Oscillation in the Interlayer Coupling of Fe Films Across Cr Films Measured by Means of Light Scattering from Spin Waves and M (H)-Curves*. Paper presented at the MRS Proceedings.
- Egelhoff Jr, W., & Kief, M. (1992). Antiferromagnetic coupling in Fe/Cu/Fe and Co/Cu/Co multilayers on Cu (111). *Physical Review B*, 45(14), 7795.
- Erwin, R. W., Rhyne, J., Salamon, M., Borchers, J., Sinha, S., Du, R., . . . Flynn, C. (1987). Magnetic structure of Dy-Y superlattices. *Physical Review B*, 35(13), 6808.
- Etienne, P., Creuzet, G., Friederich, A., Nguyen - Van - Dau, F., Fert, A., & Massies, J. (1988). Molecular beam epitaxial growth of Fe/Cr multilayers on (001) GaAs. *Applied Physics Letters*, 53(2), 162-164.
- Farrow, R., Marks, R., Harp, G., Weller, D., Rabedeau, T., Toney, M., & Parkin, S. (1993). MBE growth of artificially-layered magnetic-metal structures on semiconductors and insulators. *Materials Science and Engineering: R: Reports*, 11(4), 155-189.
- Farrow, R., Parkin, S., & Speriou, V. (1988). New approaches to epitaxy of transition metals and rare earths: Heteroepitaxy on lattice - matched buffer films on semiconductors. *Journal of Applied Physics*, 64(10), 5315-5320.
- Farrow, R., Parkin, S., Speriou, V., Bezinge, A., & Segmuller, A. (1989). *Structural and Magnetic Characterization of Rare Earth and Transition Metal Films Grown on Epitaxial Buffer Films on Semiconductor*. Paper presented at the MRS Proceedings.
- Fassbender, J., May, U., Schirmer, B., Jungblut, R., Hillebrands, B., & Güntherodt, G. (1995). Oscillatory surface in-plane lattice spacing during growth of Co and of Cu on a Cu (001) single crystal. *Physical Review Letters*, 75(24), 4476.
- Giron, F., Boher, P., Houdy, P., Beauvillain, P., Le Dang, K., & Veillet, P. (1993). Magnetoresistance in fcc (100) Co/Cu multilayers: modeling with Cu spatial thickness fluctuations. *Journal of magnetism and magnetic materials*, 121(1), 318-321.
- Goodenough, J. B. (1955). Theory of the Role of Covalence in the Perovskite-Type Manganites [La, M (II)] Mn O 3. *Physical Review*, 100(2), 564.
- Grünberg, P., Schreiber, R., Pang, Y., Brodsky, M., & Sowers, H. (1986). Layered magnetic structures: evidence for antiferromagnetic coupling of Fe layers across Cr interlayers. *Physical Review Letters*, 57(19), 2442.
- Gunther, K. (1958). On the measurement of the vapor pressure and evaporation rate of glass-forming substances. *Glastech. Ber*, 31(9), 15.
- Harp, G., Weller, D., Rabedeau, T., Farrow, R., & Toney, M. (1993). Magneto-optical Kerr spectroscopy of a new chemically ordered alloy: Co 3 Pt. *Physical Review Letters*, 71(15), 2493.
- Heinrich, B., Cochran, J., Kowalewski, M., Kirschner, J., Celinski, Z., Arrott, A., & Myrtle, K. (1991). Magnetic anisotropies and exchange coupling in ultrathin fcc Co (001) structures. *Physical Review B*, 44(17), 9348.
- Johnson, M., Purcell, S., McGee, N., Coehoorn, R., van de Stegge, J., & Hoving, W. (1992). Structural dependence of the oscillatory exchange interaction across Cu layers. *Physical Review Letters*, 68(17), 2688.
- Kwo, J., Hong, M., McWhan, D., Yafet, Y., Fleming, R., DiSalvo, F., . . . Goldmann, A. (1988). Magnetic superlattices. *Le Journal de Physique Colloques*, 49(C8), C8-1651-C1658-1655.
- Majkrzak, C. (1996). Neutron scattering studies of magnetic thin films and multilayers. *Physica B: Condensed Matter*, 221(1), 342-356.
- Mattson, J., Fullerton, E. E., Sowers, C., & Bader, S. (1995). Epitaxial growth of body - centered - cubic transition metal films and superlattices onto MgO (111),(011), and (001) substrates. *Journal of Vacuum Science & Technology A*, 13(2), 276-281.
- Nesbet, R. K. (1998). Theory of spin-dependent conductivity in GMR materials. *IBM journal of research and development*, 42(1), 53-72.
- Parkin, S., Bhadra, R., & Roche, K. (1991). Oscillatory magnetic exchange coupling through thin copper layers. *Physical Review Letters*, 66(16), 2152.

- Parkin, S. S., Hopster, H., Renard, J.-P., Shinjo, T., & Zinn, W. (1992). Magnetic surfaces, thin films, and multilayers: DTIC Document.
- Prinz, G., & Krebs, J. (1981). Molecular beam epitaxial growth of single - crystal Fe films on GaAs. *Applied Physics Letters*, 39(5), 397-399.
- Schreyer, A., Bröhl, K., Ankner, J., Majkrzak, C., Zeidler, T., Bödeker, P., . . . Zabel, H. (1993). Oscillatory exchange coupling in Co/Cu (111) superlattices. *Physical Review B*, 47(22), 15334.
- Unguris, J., Celotta, R., & Pierce, D. (1993). Oscillatory magnetic coupling in Fe/Ag/Fe (100) sandwich structures. *Journal of magnetism and magnetic materials*, 127(1), 205-213.
- Weber, W., Bischof, A., Allenspach, R., Würsch, C., Back, C., & Pescia, D. (1996). Oscillatory magnetic anisotropy and quantum well states in Cu/Co/Cu (100) films. *Physical Review Letters*, 76(18), 3424.