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Magnetic superlattices and multilayers

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Abstract

We briefly review the active areas of current research in magnetic superlattices, emphasizing later years. With recent widening use of advanced technologies, more emphasis has been made on quantitative atomic level chemical and structural characterization. Examples where the multilayer structure has been controlled, characterized and correlated with the physical properties are discussed. The physical properties are categorized according to the complexity of a structure needed to observe a particular effect. We outline a number of general important unsolved problems, which could considerably benefit from theoretical and experimental input. An extensive list of magnetic multilayer materials is provided, with references to recent publications.

Keywords: Magnetic superlattices; Multilayer materials; Physical properties

1. Introduction

Much of modern condensed matter materials physics, basic and applied research relies on the development of new materials in unusual configurations. Magnetic materials in particular provide the underpinning science for a number of technologies. Basic research in magnetism has been considerably revitalized recently by the preparation and discovery of novel magnetic materials as well as the exploitation of known materials in unusual geometries. The interest in artificially layered systems in particular, increased tremendously since the discovery of giant magneto-resistance (GMR) [1].

Metallic superlattices and multilayers have been studied for more than 60 years [2]. However, it was not to have significant impact on magnetism research until the 1980s. Advances in vacuum technologies in the 1970s resulted in major discoveries in magnetic multilayers in 1980s, and we have witnessed an explosion of the number of publications in magnetic multilayers in the 1990s (Fig. 1). Therefore, it is impossible to review properly the vast available literature [3–8] in this short article. We apologize for any omissions which are solely our oversight.

The term superlattice was coined originally to describe multilayers in which long range (larger than one bilayer thickness) structural coherence exists along the growth direction, but the two terms have been frequently used interchangeably [4]. It is this peculiar geometry that can modify their physical properties. Therefore, the amount of structural disorder which can be tolerated depends on the length scale which governs the physical properties being investigated. A comparison of the length scales relevant for structural characterization tools

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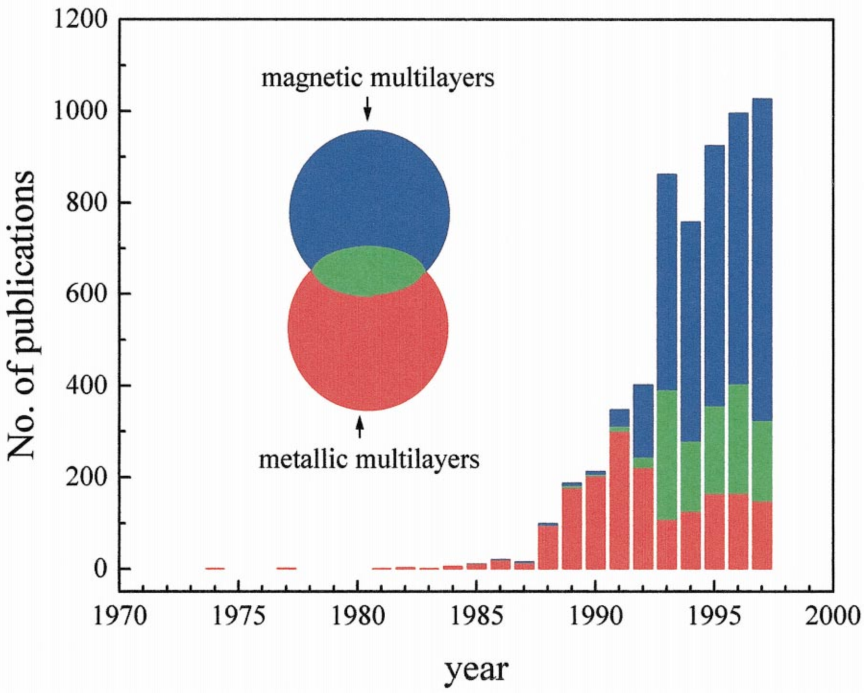

Fig. 1. Number of publications on metallic and/or magnetic multilayers, extracted from INSPEC database.

and physical properties is shown in Fig. 2. Characteristic lengths vary widely, from interatomic distances (direct exchange or Ruderman–Kittel–Kasuya–Yosida (RKKY)) to several hundreds to thousands of Å (magnetic dipolar coupling or spin diffusion length). In general, the physical phenomena in superlattices can be classified as single film, interface, proximity, coupling and superlattice effects in increasing order of sample complexity. Single film effects are due to the restriction in geometry. Proximity effects occur due to the contact between two unlike materials. Magnetic coupling across normal materials [1,11,13] has been extensively investigated. The phenomena described above require at most three layers, i.e., a superlattice structure is not needed. It is easier to observe these phenomena in superlattices because they are enhanced by the increased number of layers or because most interfaces are well protected from surface contamination. For example, perpendicular magnetic anisotropy (PMA) [14], where surface anisotropy overcomes the stronger shape anisotropy, or GMR, a consequence of antiferromagnetic coupling across non-magnetic spacer layer, were first observed in superlattices. On the other hand, superlattice effects which were the main motivators in the original stages of this field, have been observed in only a few circumstances for metals in; the structure [10], the magnon bands [13], energy bands [24], and transport properties [25]. Table 1 lists some of the major achievements in multilayers which are particularly relevant for magnetism. Magnetic superlattices and multilayers encompass almost every combination of transition metals, and to a lesser extent, rare-earth elements. An extensive list of magnetic superlattice systems is provided in Table 2 with references to recent publications.

2. Preparation and structural properties

Sputtering (DC or RF) and molecular beam epitaxy (MBE) are the main techniques used to

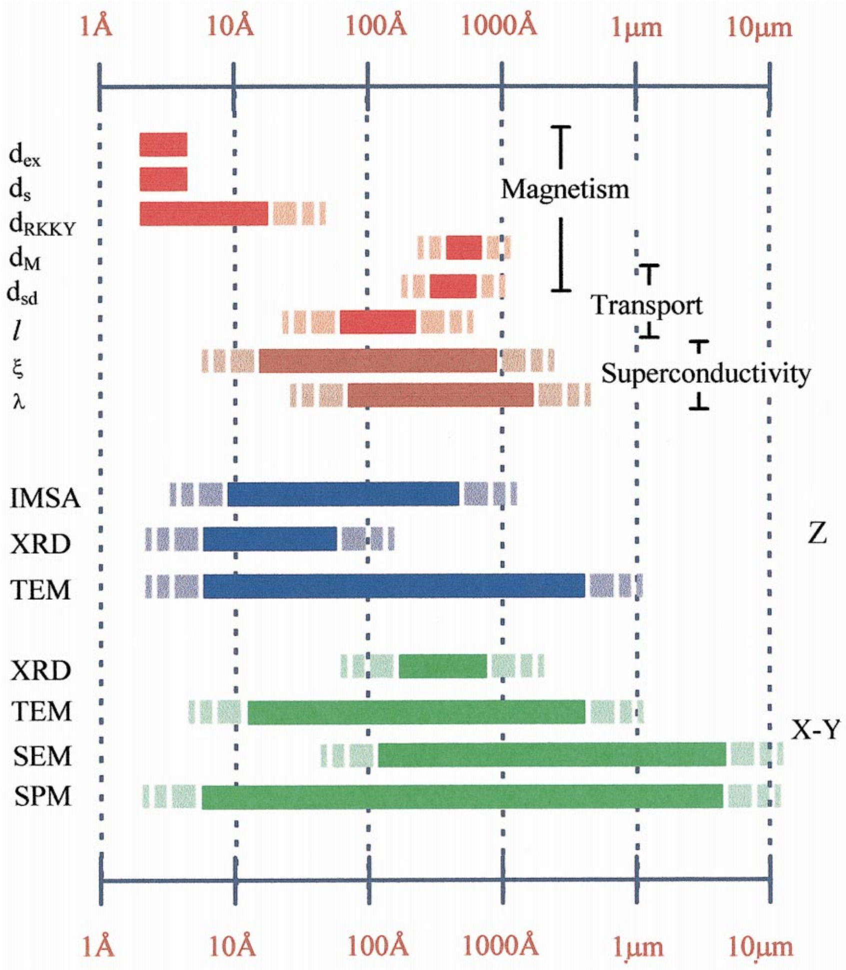

Fig. 2. Comparison of structural characterization techniques used for metallic superlattices with relevant length scales. Shaded areas represent regions of uncertainty. d_{ex} = exchange length, d_s = screening length, d_{RKKY} = RKKY length, d_M = magnetic dipolar length, d_{sp} = spin diffusion length, l = mean free path, ξ = superconducting coherence length, λ = superconducting penetration length, XRD = X-ray Diffraction, IMSA = Ion Mill Surface Analysis, TEM = Transmission Electron Microscopy, SEM = Scanning Electron Microscopy, SPM = Scanning Probe Microscopy.

fabricate metallic superlattices, while ion beam sputtering (IBS) [26] and pulsed laser deposition (PLD) [27] have been used less frequently. Growth by both MBE and sputtering followed by detailed characterization can yield complementary information.

Ultrahigh vacuum (UHV) MBE uses atomic beams to deposit epitaxial films on a substrate at an elevated temperature. Low growth rates, typically submonolayer per second, combined with surface migration enable layer-by-layer growth. Film growth, far from thermodynamic equilibrium, is governed mainly by the surface kinetics occurring when the impinging atoms encounter the substrate. UHV MBE has the unique advantage that it allows in situ surface characterization by sensitive diagnostic tools such as reflection high energy electron diffraction (RHEED) and Auger electron spectroscopy (AES).

Sputtering permits higher throughput, is easy to rate-control and allows tunability of the energy

Table 1
Chronology of selected achievements in multilayers

Year		Ref.
1935	Fabrication of metallic superlattices and multilayers	[2]
1978	Anomalous magnetization in Cu/Ni	[9]
1980	Lattice mismatched superlattices	[10]
1981	RKKY coupling in Cu/Ni	[11]
1982	Absence of 2D magnetism in Cu/Ni	[12]
1983	Magnon bands in magnetic superlattices	[13]
1985	Perpendicular magnetic anisotropy in Co/Pd	[14]
	Spin injection experiment	[15]
1986	Spiral coupling in Dy/Y	[18]
	Oscillatory coupling in Gd/Y	[19]
	Anti-ferromagnetic (AF) coupling in Fe/Cr sandwiches	[16]
	Inequivalence of magnetic and structural roughness	[17]
1988	Giant Magneto-Resistance (GMR)	[1]
1989	AF coupling in Co/Cu	[20]
1990	Oscillatory coupling in GMR materials	[21]
1991	Perpendicular transport in multilayers	[22]
	Phase diagram of AF coupled ferromagnetic layers	[23]
1992	Superlattice energy bands in Ag/Au by photoemission	[24]
1994	Superlattice effect in transport in Co/Ni	[25]

distribution of particles arriving at the substrate. The presence of sputtering gas generally excludes the use of in situ structural characterization techniques and is more susceptible to contamination. However, it is fair to state that the structural and physical properties of metallic superlattices prepared by both techniques are comparable, if the same care is taken in the growth process. Probably the reason for this is that, contrary to semiconductors, most properties of metals are relatively insensitive to small amounts of contamination.

Metallic superlattices have been grown from a large variety of combinations of metallic elements, without consideration regarding their crystallographic structures. On one hand, elements that are closely lattice matched and have the same crystal structure, generally have equilibrium thermodynamic phase diagrams forming continuous sets of solid solutions [28]. Therefore, they are driven thermodynamically towards interdiffusion, although thin film growth is kinetically limited. On the other hand, as known for many years, lattice matching is not a necessary condition for epitaxy [29]. Therefore, if the superlattice components form no alloys, it may be expected that they will be

Table 2
Characterization on metallic magnetic multilayers. Code: Sp = Sputtering, MBE = Molecular Beam Epitaxy, Ev = Evaporation, IBS = Ion Beam Sputtering, PLD = Pulsed Laser Deposition, Ed = Electrodeposition, XRD = X-Ray Diffraction, ND = Neutron Diffraction, IS = medium/low energy Ion Scattering, RBS = Ratherford Back Scattering, TEM = cross sectional Transmission Electron Microscopy, SPSEE = Spin Polarized Secondary Electron Emission, PE = Photoemission, XMCD = X-ray Magnetic Circular Dichroism, XFS = X-ray Fluorescence Spectroscopy, XES = X-ray Emission Spectroscopy, XAS = X-ray Absorption Spectroscopy, DAFS = Diffraction Anomalous Fine Structure Spectroscopy, XRMS = X-ray Resonance Magnetic Scattering, VSM = Vibrating Sample Magnetometer, SQUID = Superconducting Quantum Interference Device, AGFM = Alternating Gradient Force Magnetometer, MOKE = Magneto Optical Kerr Effect, MO = Magneto-Optical, O = Optical, KM = Kerr Microscopy, MS = Conversion Electron Mössbauer Effect, FMR = Ferro Magnetic Resonance, TM = Torq Magnetometer, NMR = Nuclear Magnetic Resonance, MC = Magnetic Coupling, MR = Magneto-Resistance, GMR = Giant Magneto-Resistance, AMR = Anomalous Magneto-Resistance, MA = Magnetoic Anisotropy, PMA = Perpendicular Magnetic Anisotropy, M = Magnetic Moment, DOS = Density of States

System [Ref.]	Deposition	Characterization	Properties
Fe/Ti [35,36]	Sp	XRD TEM VSM MS	MA MR
Fe/V [37–39]	Sp [0 0 1]	XRD XES SQUID	GMR AMR DOS
[40]	Sp [0 0 1][2 1 1][1 1 0]	MOKE XMCD	M
Fe/Cr [1,41,42,45–48]	MBE [0 0 1][1 1 0] poly	XRD ND MS MOKE	GMR MA MC
[49–56]	Sp [0 0 1][2 1 1] poly	XRD ND SQUID MOKE	GMR MA MC
Fe/Cu [57,58]	PLD [0 0 1]	MOKE PE XMCD	M DOS
Fe/CuZr [59]	MBE	MOKE KM	MC
Fe/Zr [60]	Sp	XRD MS	M
Fe/Nb [61]	Sp	XRD	GMR

Table 2 (continued)

System [Ref.]	Deposition	Characterization	Properties
Fe/Mo [62,63]	Sp	XRD VSM SQUID	GMR
Fe/Pd [64]	MBE [0 0 1]	TEM SQUID AGFM KM	MA
Fe/Ag [65]	Sp	XRD TEM VSM	GMR
Fe/Ir [66]	MBE [0 0 1]	DAFS	
Fe/Pt [67,68]	Sp Ev [0 0 1] poly	XRD VSM TM MS	MA
Fe/Au [69–72]	Sp Ev MBE [0 0 1][1 1 1]	XRD IS VSM TM MS FMR	PMA MR
Fe/Si [73,26]	IBS [0 0 1][1 1 0]	XRD TEM XFS VSM	MC
Fe/Ge [74]	MBE	SPSEE	MC
Fe/Gd [75]	Ev		MR
Co/Ti [76,77]	Sp	XRD TEM VSM	MA
Co/V [78]	Sp	FMR	MA
Co/Cr [81,79,80]	MBE [0 0 1][1 $\bar{1}$ 0]	MOKE	PMA MC MR
Co/Cu [82,83,30]	MBE [111]	XRD IS FMR	GMR MA
[84–91]	Sp	XRD XAS XES VSM AGFM	GMR MR
[92]	Ev	XRD TEM RBS MOKE	GMR
[93]	IBS	XRD VSM FMR	MC
[94–96]	Ed	XRD TEM	GMR
Co/Zr [97]	Sp	XRD FMR	MO O
Co/Pd [98]	SP	FMR	PMA
Co/Ag [99,100]	SP		GMR
Co/Ir [101]	IBS	XRD	GMR
Co/Pt [102–105]	Sp	XRD MOKE VSM	MO O DOS
Co/Au [106,107]	Ev MBE [111]	XRD MOKE	MR PMA M
Ni/Ag [108,109]	SP	VSM FMR XRMS	MA MC
Ni/Pt [110]	Ev	XRD TEM MOKE	PMA
NiFe/Cu [111,112]	Ev Sp	XRD TEM	GMR
NiFe/Mo [113]	SP	XRD	
NiFe/Ag [114]	SP	XRD MS	M MR
NiFe/Au [115]	Sp	XRD	
CoNi/Cu [116,117]	Ed		GMR
Fe/Ni [118,119]	SP [0 0 1]	XRD SQUID	M
Fe/Tb [120,121]	Sp	XRD ND SQUID MOKE MS	PMA M
Co/Ni [122,123]	Sp		AMR
[25,124–126]	MBE [111]	XRD	MR
Co/SmCo [127]	Sp	XRD TEM SQUID	M
Dy/Sc [128]	MBE [0 0 1]	XRD	MR
Dy/Lu [129]	MBE [0 0 1]	XRD	
Se/Eu [130]	MBE	XRD	M
Y/Tb [131]	MBE [0 0 1]	NMR	
Ho/Gd [132]	MBE [0 0 1]	XRD ND	M
Ho/Tm [133]	MBE [0 0 1]	XRD ND	M
Ho/Lu [134]	MBE [0 0 1]	XRD ND	M
Er/Lu [135]	MBE [0 0 1]	XRD ND	M

more segregated. Since the first growth of lattice mismatched metallic superlattices from the eutectic Nb–Cu system [10], many more systems have been fabricated. However, atomic level interdiffusion is found in even immiscible systems [30].

Another important issue is that the growth of a superlattice is somewhat different from that of a bilayer. The structure is affected by the momentary substrate and the temperature on which a layer is growing, i.e., different interfaces and layers have different growth conditions. At elevated growth temperatures, annealing and interdiffusion may occur in the buried layers. Therefore, it is important to characterize the structure once the whole superlattice is grown.

For relatively thick multilayers, detailed knowledge of the interface structure is not important because physical properties are not significantly affected by interface quality. On the other hand, multilayers with constituents approaching single monolayer (ML) level, are routinely fabricated these days. In such cases, structural characterization is crucial. Non-destructive diffraction techniques, such as X-ray diffraction (XRD), are commonly used to analyze multilayered structure [10]. Powerful tunable photon sources are capable of element specific characterization [31] and polarized photons or neutrons are available to probe the magnetic structure [31,51]. Since quantitative diffraction studies require modeling and a priori knowledge of the probed length scale, complementary techniques, such as cross-sectional transmission electron (TEM) or scanning probe microscopies (SPM) are helpful.

The major types of structural imperfection present in superlattices are interfacial roughness, interdiffusion, imperfect crystallinity, and crystalline orientation. The distinction between interdiffusion and roughness is artificial, since at the atomic level the concept of interdiffusion is somewhat meaningless. At short length scales, smaller than the lateral coherence length of a particular probe, an interface with roughness ‘looks’ like a homogeneous interface with an average scattering function given by the relative proportion of the constituents. In a naive interpretation, interdiffusion affects only the peak intensities, while layer thickness fluctuations broaden the peaks [32]. Rocking curve widths are affected by the angular distribution of crystallites and crystalline orientation, while variations in interatomic spacing change the peak position. In realistic situations, however, there is no such clear distinction between the particular type of disorder and its effect on a particular feature; all diffraction features are affected to some degree. Therefore, quantitative analysis of diffraction data requires comparison to simulated diffraction patterns with detailed modeling of defect structures [33].

Superlattices are routinely checked using laboratory X-ray diffractometers (Table 2), while synchrotron sources provide tunability, polarization and increased intensity, to improve diffraction quality [39,41,84,109] or provide diffuse scattering [82,87,115] data. Conventional diffraction (specular) and diffuse scattering (off specular) data contains complementary information. The specular peaks contain information on defect structures along the growth direction, while the lateral length scale being probed is rather uncertain, whereas diffuse scattering data shed light on lateral correlation lengths. Quantitative disorder parameters can be extracted from the data by detailed refinement techniques [33]. There are exploratory reports on the use of ion scattering to investigate interface roughness by low [30] and medium [69] energy ion scattering (LEIS, MEIS).

Powerful tunable photon sources become more important in spectroscopic areas to probe the superlattice electronic structure, i.e., X-ray fluorescence spectroscopy (XFS) [73], X-ray emission spectroscopy (XES) [39], X-ray absorption spectroscopy (XAS) [88], diffraction anomalous fine structure spectroscopy (DAFS) [66], X-ray resonance magnetic scattering (XRMS) [109] and near edge X-ray absorption fine structure (NEXAFS) [66]. The magnetic profile could be different from the chemical profile of the superlattice [17,34]. Magnetic structure of interfaces can be probed by X-ray magnetic circular dichroism (XMCD) and neutron diffraction techniques, which are reviewed by other authors (Stirling, *X-Ray Magnetic Scattering*; Stöhr, *X-Ray Magnetic Dichroism Studies of Magnetic Anisotropies*; Felcher and Ankner, *Polarized Neutron Reflectivity*).

3. Physical properties

Magnetic superlattices composed of ferromagnetic/non-magnetic (F/N) materials have been studied for the effects of dimensionality, magnetic anisotropy associated with the F/N interface, magnetic coupling through the non-magnetic spacer layer, and to a much lesser extent, for superlattice electronic or spin structure effects. Ferromagnetic/ferromagnetic (F/F) or rare-earth superlattices attracted much less attention. In this section, we will review the physical properties in increasing sample complexity and will give as an example the most outstanding recent development.

3.1. *Interface/proximity effect; perpendicular magnetic anisotropy*

Metallic multilayers composed of alternating layers of a ferromagnetic transition metal (FT = Fe, Co, Ni) and noble metals (NM = Cu, Ag, Pd, Pt, Au) exhibit perpendicular magnetic anisotropy (PMA) and maybe useful as magneto-optic recording media. In these multilayers, interfacial magnetic anisotropy may be perpendicular and is controlled by the nature of interface. The interfacial spin is well described [136] by the interface hybridization of electronic d states between FT and NM and gives rise to this out-of-plane spin orientation. This PMA is an example of an interface and/or proximity effect, which does not require multilayer structure but it is commonly investigated for convenience in multilayers. We will leave more detailed review on this subject to other authors (Freeman, Wu, *Surface Magnetic Anisotropy*).

The use of Pd as the nonmagnetic element (Fe/Pd [64], Co/Pd [14,98]) is particularly interesting. Although Pd is non-magnetic it is well known to possess unusually high susceptibility due to a large Stoner enhancement factor. Ferromagnetic impurities or proximity to ferromagnetic materials can produce a magnetic moment in otherwise nonmagnetic Pd. Co/Pd, the first system showing PMA [14], is still investigated [98] and since the Pd polarization is sensitive to structural defects, considerable emphasis is made on structural characterization [64]. Co/Pt [102–105] multilayers attracted recent attention because of the simultaneous large magneto-optical (MO) Kerr rotation and PMA which were interpreted using theoretical band structure calculations [103]. The high potential in MO applications motivated the effort to optimize physical properties such as lowering the Curie temperature by introducing Ni in the Co layer or at the interface [102,103]. PMA has also been observed in Fe/Au [71], Co/Au [107,137], Co/Cr [79], and Fe/Tb [120,121] superlattices. Another manifestation of interaction at interfaces is found in Co/SmCo [127] exchange spring magnets, CoO/NiO [154,155] exchange biased superlattices or FeF_2/CoF_2 [153] antiferromagnets.

An area highly neglected is that of magnetic proximity effect. Although some theoretical effort [138,139] was devoted to this in the early 1970s, very little experimental work has emerged. Contrary to superconductivity, investigating the short length scale spacial dependence of the magnetization is not easy, although some experiments were performed using polarized neutron reflectivity [17,34]. With the advent of more powerful neutron sources and the development of novel synchrotron techniques [140] the magnetic proximity effect can finally be tackled.

3.2. *Coupling effect; giant magneto resistance*

Several types of magnetic coupling across nonmagnetic spacer layers were investigated in the 1980s (Table 1). The discovery of GMR in Fe/Cr [1], shortly after the discovery of antiferromagnetic (AF) coupling [16], together with the oscillatory coupling [21], had an enormous impact in the area. We will only briefly summarize the current status for better understanding of the rest of the manuscript, leaving the more detailed review to other authors (Stiles, *Interlayer Magnetic Coupling*; Celotta, Stiles, Unguris, Pierce, *Influence of Interfacial Roughness on Magnetic Coupling of Fe/Cr Layered Structures*; Bass, Pratt, *Current Perpendicular Magnetoresistance in Magnetic Metallic Multilayers*). There are many experimental (see Table 2) and theoretical [141] investigations dedicated to this area because of technological implications in magnetoresistive devices. The basic mechanism responsible for this effect is the low field antiferromagnetism of adjacent Fe layers with the high field ferromagnetic alignment. This, together with spin-dependent scattering (not spin flip) [142] gives rise to additional scattering in zero field compared to high field. GMR is expected to be bigger in the perpendicular transport which is difficult to measure in thin films, although this geometry is now being probed by several methods [22,143,144].

Fe/Cr is one of the most extensively investigated superlattices and has also been studied in trilayer 'spin valves' [147]. Oscillations in the AF coupling as a function of spacer layer thickness have been reported in wedged samples (short period ~2 ML) [145,43] or in superlattices (long period ~11–18 Å) [21]. The magnitude of GMR varies greatly regardless of deposition method or crystalline orientation (being as high as 220% [44]), even for a fixed configuration. The discrepancies have not yet been clearly understood, although it has been implied that details of the structure are at the root of the problem. Although significant effort was dedicated to characterize the interface disorder, mostly by XRD, the results seem apparently inconsistent. Superlattices with different interface roughness were fabricated by changing the growth temperature or buffer layers in MBE or by varying the deposition pressure in sputtering. As interface roughness increased (as extracted from quantitative XRD analysis), GMR decreased in MBE samples [41], but either increase [54] or decrease [146] in sputtered polycrystalline samples. Another controversial claim was GMR oscillation with Fe layers thickness [46], although relatively big GMR has been consistently reported for thinner Fe layers (less than 15 Å). These reiterate our incomplete understanding of characterization tools and defect structure in superlattices with a few MLs of alternating elements. Cr spacer layers in Fe/Cr deserve special attention because of the possible connection to the antiferromagnetism of bulk Cr. Although the magnetic structure of the Cr and Fe layers have been studied extensively [49–52], the existence of antiferromagnetism in thin Cr spacer layers is not yet clearly identified. Moreover, GMR is observed in superlattices with a normal metal spacer.

Co/Cu, another well studied superlattice exhibiting similar oscillatory AF coupling and GMR has a normal metal spacer. The higher room temperature GMR and lower saturation field make it more attractive for application. Co/Cu superlattices were fabricated by many techniques (MBE [30,82,83], sputtering [84–91], evaporation [92], IBS [93], and electrodeposition [94–96]) and the structure was analyzed quantitatively by combining specular, off-specular, and anomalous X-ray scattering [84,87]. The interface roughness manipulated by changing substrate temperature [85], or the interface width by codeposition [89] decreases GMR with increasing interface roughness, probably due to interdiffusion. This is consistent with low-energy ion scattering experiments showing significant surface diffusion for Co/Cu(1 1 1) even at room temperature [30]. As in Fe/Cr, reduced GMR was reported with increasing Co thickness [9]. In addition to the well-studied GMR, other properties, such as in-plane magnetic anisotropy [83], spin wave resonance [93] and electronic density of states (DOS) near buried interfaces [88], and interference of quantum well states due to ferromagnetic layer [148], were reported. Even nanowire fabrication by electrodeposition through nanopore membranes has been reported for unconventional current perpendicular to the plane (CPP) measurement [94,96].

GMR and AF coupling has also been reported in many other systems [37,63,65,71,99–101,107, 112,116] although the GMR is small and/or only observed at relatively thin ferromagnetic layer thickness. It is interesting to note that antiferromagnetic coupling, an underlying mechanism for GMR, has been observed also through amorphous (Fe/CuZr [59]) and semiconducting (Fe/Si [26,73], Fe/Ge [74]) materials. This suggests that GMR and AF coupling seem to be universal phenomena, not specific to a particular material system.

A number of other coupling effects are present, which, however, have received considerably less attention. These include magnetic-structure investigation in rare-earth superlattices [128–135, 149,150], and magnetic investigation of rare-earth transition metal superlattices [151].

3.3. *Superlattice effects*

Superlattices alternating a few MLs with sharp atomic level interfaces could provide a new challenge to fundamental physics. Superlattice energy bands have already been observed in Ag/Au [24] by photoemission and X-ray L-emission spectra of the 3d band of Fe/V [39] seemed to be in agreement with first-principle band structure calculations. In Fe(1 ML)/Cu(1 ML) [58] superlattices it was claimed from spin-resolved photoemission, that the dispersion of Fe-type majority bands along the Γ–Δ axis indicates the presence of bands as a consequence of the unit cell doubling in the growth direction. With indications that the interface roughness may be controlled at the atomic level and that the electronic structure changes accordingly, it is interesting to investigate possible new physical phenomena associated with this.

Finally, it should be noted that observation of superlattice effects in the physical properties such as electrical transport is unusual. Oscillations in the residual resitivity and magnetoresistance of Co/Ni [124,125] were interpreted in terms of superlattice effects [126,152] due to the fact that they occur as a function of the individual layer thicknesses, the total multilayer period, and depend on the number of bilayers.

4. Open questions

It is perhaps fitting to highlight that these materials are in need of new theoretical and experimental paradigms. Disorder is a key ingredient in all these materials. Although striving for even higher perfection is a commendable effort, it is safe to state that absolute perfection will not be achieved in the near future. As suggested above [17,34] disorder affects at different length scale different physical properties. Therefore, developing theories and experimental situations which probe the effect of disorder at varying length scale is of crucial importance. The theoretical treatment of spin scattering at interfaces, along with realistic treatments of defects and disorder is lacking [6]. It seems that experimental results are insufficient to distinguish between scattering by magnetic atoms or the magnetic field profile at the interface. In addition to this, the general problem of understanding a realistic inhomogeneous electron gas (with spin) is essentially an open one. For instance, in the field of magneto transport and coupling, the irreproducibility from lab to lab, the role of interfacial versus bulk scattering, the dependence of transport on various structural defects, the connection to crystallographic orientation, the changes with growth method etc., are all in need of research or are controversial.

The investigation of the magnetic proximity effect, especially due to the myriad of length scale present, is possibly amenable to investigation with the new powerful techniques being developed [31]. Engineering novel magnetic phases, in which interfacial tunning is used to modify naturally occurring structures holds much promise. Investigating the competition between different magnetic phases holds the promise of development of unusual magnetic materials. Small, low-dimensional structure have magnetic energies which are comparable to the temperature and possibly the large magnetic fields currently being developed. This will allow the exploration of completely novel thermodynamic phase diagrams.

Finally, the question of how (or even if) superlattice effects manifest themselves in the measurement of the physical properties of superlattices is an interesting one. For instance, do extended wave functions exist in the perpendicular direction or are they localized due to the unavoidable introduction of defects and disorder? The role played by energy gaps and localized states is yet to be clarified. Although much of the motivation for this type of work is basic in nature, important applications which have moved into the commercial market in a short time period have already emerged. Clearly, many interesting phenomena are envisioned and although it is hard to predict, applications are likely to emerge.

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