Surface Science Reports 63 (2008) 400–425

Contents lists available at ScienceDirect

Surface Science Reports

journal homepage: www.elsevier.com/locate/surfrep

Interface effects in spin-polarized metal/insulator layered structures

J.P. Velev[a], P.A. Dowben[a,*], E.Y. Tsymbal[a], S.J. Jenkins[b], A.N. Caruso[c]

[a] *Department of Physics and Astronomy, Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68588, USA*
[b] *Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, United Kingdom*
[c] *Department of Physics, University of Missouri, Kansas City, MO 64110, USA*

ARTICLE INFO

Article history:
Accepted 16 June 2008
editor: U. Diebold

Keywords:
Magnetic tunnel junctions
Interface states
Spin polarization
Multiferroics

ABSTRACT

Recent advances in thin-film deposition techniques, such as molecular beam epitaxy and pulsed laser deposition, have allowed for the manufacture of heterostructures with nearly atomically abrupt interfaces. Although the bulk properties of the individual heterostructure components may be well-known, often the heterostructures exhibit novel and sometimes unexpected properties due to interface effects. At heterostructure interfaces, lattice structure, stoichiometry, interface electronic structure (bonding, interface states, etc.), and symmetry all conspire to produce behavior different from the bulk constituents. This review discusses why knowledge of the electronic structure and composition at the interfaces is pivotal to the understanding of the properties of heterostructures, particularly the (spin polarized) electronic transport in (magnetic) tunnel junctions.

Contents

* Corresponding author. Tel.: +1 402 472 9838; fax: +1 402 4722879.
E-mail address: pdowben@unl.edu (P.A. Dowben).

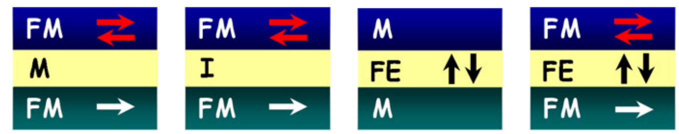
0167-5729/$ – see front matter
doi:10.1016/j.surfrep.2008.06.002

1. Introduction

Major advances in thin-film deposition techniques and characterization have enabled the development of materials which bring new functionalities to traditional devices or even novel device paradigms. In particular, advances in molecular beam epitaxy and pulsed laser deposition techniques have made it possible to manufacture layered heterostructures with nearly atomically abrupt epitaxial interfaces and individual layer thickness of the order of nanometers. In such nanoscale heterostructures, the ratio of interface to bulk material is comparable, which, in addition to the high quality of the interfaces, ensures that the properties of these heterostructures are interface dominated.

The study of artificial materials such as layered heterostructures falls somewhat out of the scope of traditional disciplines. Traditional materials science has not generally been concerned with interfaces. Surface science is mainly focused on the interfaces between different phases, such as the solid and vacuum interface. The small dimensions of heterostructures also require a microscopic approach on the level of individual atoms. These methods are a prerogative of condensed matter physics and quantum chemistry, which fields are normally not focused on applications. However, the development of nanoscale heterostructures has done much to revitalize all these fields, and infuse them with interdisciplinary surface and interface science [1–4]. One of the most prominent subfields has been the field of spin electronics (or spintronics), which promised to revolutionize electronics by introducing a new degree of freedom, electron spin, to be exploited simultaneously along with the electron charge [5,6]. Although not all of the suggested potential for applications has been realized, existing applications are already having a tremendous impact in information technology with applications such as high-density magnetic recording [7,8], and magnetic random access memory (MRAM) [9,10].

The task of spintronics, from its onset, has been to search for solutions beyond traditional electronics, which is reaching a limit in natural scalability. Thus, spintronics is intentionally on the 'lookout' for emerging materials that bring new functionalities. A very broad range of materials have been considered as possible candidates for spintronics applications, such as ordinary semiconductors [11–13], ferromagnetic semiconductors [14–16], organic semiconductors [17–19], single molecules [20,21], single molecular magnets [22,23], organic-based magnetic semiconductors [24,25], carbon nanotubes [26,27] and graphene [28,29]. Recently, thin-film ferroelectrics have aroused significant interest due to their technological application in ferroelectric random access memory (FERAM) devices [30,31]. These developments have broadened into a search for a new class of multifunctional spintronics materials, *i.e.*, materials that can perform more than one task, or that can be manipulated by several independent stimuli [32–34]. Multifunctional materials exhibit two or more (coupled) ferroic orders, such as ferromagnetic, ferroelectric, or ferroelastic and are often referred to as multiferroic. The relative scarcity of single-phase multiferroic materials [35] is circumvented by the emerging field of artificial multiferroics that combine different ferroic materials in the same heterostructure [36,37].



(a) SV: GMR (b) MTJ: TMR (c) FTJ: GER (d) MFTJ: 4-resistance

Fig. 1. Heterojunction structure and properties: (a) magnetic spin valve (SV), resistance change in magnetic field—giant magnetoresistance (GMR); (b) magnetic tunnel junction (MTJ), tunneling magnetoresistance (TMR); (c) ferroelectric tunnel junction (FTJ), resistance change in electric filed—giant electroresistance (GER); and (d) multiferroic tunnel junction (MFTJ), resistance change in both electric and magnetic fields (4-resistance). The ferromagnetic (FM), ferroelectric (FE), paramagnetic metal (M) and insulating (I) layers are indicated where appropriate.

At the heart of spintronics is the dependence of the physical properties of materials (in particular electron transport) on electron spin. Scientific interest in spin-dependent transport originates from the work of Mott [38], who realized that at low temperatures the electric current in ferromagnetic metals is a sum of two independent spin currents, carried by majority- and minority-spin electrons. Much later, experiments by Tedrow and Meservey [39], who studied tunneling from a ferromagnet through an insulator into a superconductor, demonstrated the presence of non-vanishing spin polarization (SP) of the tunneling current. This latter discovery may be considered as the first demonstration of a functioning spintronics device. Four years later, Jullière observed the effect of tunneling magnetoresistance (TMR) in a magnetic tunnel junction (MTJ) [40], shown in Fig. 1b. Unfortunately, the values of TMR observed were small and not reproducible, hampered by problems in making extremely thin and pinhole-free insulating layers.

The onset of sudden increase of interest in layered heterostructures can be traced to the discovery of the interlayer exchange coupling (IEC) [41,42]. Interlayer exchange coupling takes place in magnetic multilayers, in which ferromagnetic layers are separated by a nonmagnetic spacer. It can be conducting as well as insulating, as shown in Fig. 1a, b. Interlayer exchange coupling was first observed for metallic spacers [41] and was found to oscillate as a function of spacer thickness [42]. Experimental observation of the interlayer exchange coupling across an insulator has been much more challenging, because producing a thin uniform insulating barrier is rather difficult. There are only a few reports of measurements of the coupling across a tunnel barrier [43–45]. The interlayer exchange coupling can be explained either in terms of the spin torque exerted by one ferromagnet on the other [46–48] or in terms of the induced density of states in the spacer by the ferromagnets [49,50].

Antiferromagnetic interlayer exchange coupling in magnetic multilayers at certain thicknesses of the spacer led to the discovery of giant magnetoresistance (GMR), *i.e.* a large change in the resistance of the multilayer when the relative ferromagnetic layer magnetization is altered from antiparallel to parallel by an external magnetic field [51,52]. GMR received a great deal of attention because of very large values of magnetoresistance (MR) (for reviews of GMR see Refs. [53–60]). The typical GMR values of tens of percent at room temperature and hundreds