58918-00-105
59001-00-105

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Chun-Yeol You, C.H. Sowers, A. Inomata, J. S. Jiang, S.D. Bader, and D. D. Koelling

Materials Science Division
Argonne National Laboratory, Argonne, IL 60439

Proceedings of the 43rd Annual Conference on Magnetism and Magnetic Materials, Miami, FL, November 9-12, 1998

Work supported by the U.S. Department of Energy Division of Basic Energy Sciences-Material Sciences under contract No. W-31-109-ENG-38.

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Oscillation period of the interlayer coupling for epitaxial $Fe/Cr_{1-x}V_x(100)$ and (211) superlattices*

Chun-Yeol You, C. H. Sowers, A. Inomata, J. S. Jiang, S. D. Bader, and D. D. Koelling

Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

The microscopic origin of the 18-Å period in the oscillatory interlayer exchange coupling of Fe/Cr(100) and (211) superlattices is investigated by alloying the Cr spacer with V to alter its Fermi surface. The addition of V increases or decreases in size the various Fermi surface calipers that are candidates for governing the oscillation period, such as those that span the ellipse, lens, octahedron, and nested sheets. Epitaxial sputtered superlattices of (100) and (211) orientation were grown and characterized via magnetoresistance measurements as a function of spacer layer thickness for different V-doping levels. A small decrease of the oscillation period is found experimentally which strongly implicates the N-centered *ellipse* as the origin of the 18-Å period in Fe/Cr superlattices.

* Work supported by the US DOE Basic Energy Sciences – Materials Sciences under Contract No. W-31-109-ENG-38.

I. INTRODUCTION

The oscillatory interlayer exchange coupling between two ferromagnetic layers through spacer layers has recently been extensively studied due to both fundamental interest in the physics of giant magnetoresistance (GMR) materials and applied interest associated with the development of new magnetic sensors and non-volatile memory arrays.[1] It is now broadly accepted that the period of the interlayer exchange coupling is determined by particular Fermi surface calipers of the spacer materials.[2] Chromium, being a transition metal, has a complicated Fermi surface with a diversity of such spanning vectors; however, none exhibit precisely the 18-Å experimentally measured value for what is commonly referred to as the 'long' period. In contrast to this situation, the origin of the ~2 monolayer 'short' period of Cr is widely recognized as being due to the nesting vector that also gives rise to the antiferromagnetism of Cr.[3]

The origin of the 18-Å *long* period of the interlayer exchange coupling exhibited by Fe/Cr superlattices of both (100) and (211) epitaxial orientation[4] remains controversial despite intensive experimental[5] and theoretical[6-10] investigations. Van Schilfgaarde[6] argued that *aliasing* of the second harmonics of the short-period oscillation gives rise to the long period, and predicted a rapid decrease of the period with 10 % of V for the (001) orientation. Koelling[7] suggested that the relatively isotropic *d*-derived *lens* can provide the *k*-space caliper to explain the crystallographic orientational insensitive[4] of the long period. Mirbt[8] identified an octahedron-coupling caliper based on a CsCl structure that is the same as the Cr bcc structure but with two atoms per unit cell to account for the antiferromagnetism of Cr. Stiles[9] and Tsetseris[10] identified the *sp*-derived *ellipse* centered at the *N* point of the Fermi surface as providing the underlying caliper for the long period. Li *et al.* experimentally implicated the lens calipers, based on photoemission experiments that monitored the emergence of quantum-well features that are

believed to underlie the coupling. However, Stiles[9] subsequently reinterpreted the photoemission results as being due to quantum wells that are not spin-polarized and therefore not associated with the coupling.

The motivation of the present work is to address this issue via alloying the Cr spacer in order to modify its Fermi surface topology. It is known that adding elements having a smaller (V) or larger (Mn) number of valence electrons than Cr can be interpreted within a rigid-band approximation.[11] Alloying effectively increases (Mn) or decreased (V) the Fermi energy of Cr. Since alloys of Cr-Mn exhibit antiferromagnetism, we limited our experiments to alloys of V only.

Similar studies[12,13] have been performed for Co/Cu superlattices, where Cu, of course, has a much simpler Fermi surface. Parkin *et al.*[12] and Bobo *et al.*[13] modified the Cu Fermi surface via alloying with Au, Fe, or Ni to investigate the variation of the oscillation period. In this system the relationship between the modification of the period and the Fermi-surface caliper with alloying can be explained quite convincingly using a simple band model.

In the present work, we grow epitaxial superlattices of $Fe/Cr_{1-x}V_x(100)$ and (211), with x = 0.085 and 0.20, on MgO(100) and (110) substrates, respectively, by dc magnetron sputtering.[4] The GMR was measured to monitor the periodicity as a function of spacer thickness. We find that the period of oscillation decreases only modestly with increasing V-doping, which strongly suggests that the ellipse centered at the *N*-point of the Fermi surface is the likely origin of the long-period oscillation in the Fe/Cr GMR system.

II. EXPERIMENTAL PROCEDURE:

$Fe/Cr_{1-x}V_x$ (x = 0.085, 0.20) superlattices were grown by dc magnetron sputtering onto epitaxially polished single crystal MgO(100) and (110) substrates. The sputtering chamber has a base pressure of ~ 1×10^{-7} Torr, and the 2-in. planar magnetron sputtering guns were operated in an Ar gas pressure of 4 mTorr and a target-substrate distance of 3.5 inch. A 100-Å Cr buffer layer was initially deposited at a substrate temperature of 400 °C to establish the epitaxial orientation with the substrate. The substrate was cooled to 100 °C and the superlattice was grown. To make the alloy layer, we fabricated mosaic targets. The number of layers was adjusted so that the total superlattice thickness was constant about ~1000 Å. The structures were characterized by x-ray diffraction using Cu K_α radiation, and the magnetic properties were measured by means of the longitudinal Kerr rotation. The magnetotransport properties were studied by a standard, four-probe technique. The concentrations of V in the Cr matrix were determined by the induction coupled plasma (ICP) analytic technique. More details on the experimental procedure are published elsewhere.[4]

III. EXPERIMENTAL RESULTS:

Since Cr and V are completely soluble in one another over the whole concentration range, the structural properties of $Fe/Cr_{1-x}V_x$ can be predicted to very similar with those of Fe/Cr. The x-ray diffraction results of the $Fe/Cr_{1-x}V_x$ superlattices are similar to those of Fe/Cr superlattice that were studied previously.[4] In the high-angle x-ray diffraction spectra, there are no unexpected peaks present that would indicate the presence of additional phases or orientations. Rocking curves about the $Fe/Cr_{1-x}V_x$(100) and (211) have full width at half maximum (FWHM) of < 2°

for various $Cr_{1-x}V_x$ thicknesses. The results indicate a high degree of crystallographic orientation of the samples.

The magnetic properties of the alloy superlattices are also very similar to those of the Fe/Cr superlattices. The (211)-oriented alloy superlattices have both the expected biaxial magnetocrystalline anisotropy and uniaxial anisotropy originating from the surface anisotropy.[14,15] The magnetotransport was measured at room temperature. The dependence of GMR on the thickness of $Cr_{1-x}V_x$ layers was shown at Fig. 1 (a) ~ (d) for each crystalline orientation and V concentration. As shown in Fig. 1, periods of ~16 Å (x = 0.085) and ~15 Å (x = 0.20) for Fe/$Cr_{1-x}V_x$ (100), and ~17 Å (x = 0.085) and ~16 Å (x = 0.20) for Fe/$Cr_{1-x}V_x$ (211) were found. Thus, a slight decrease in the value of the period with V-doping was observed for each crystallographic orientation.

IV. DISCUSSION AND RESULTS:

The band structure along the high symmetry Δ and Σ directions for Cr group transition metals is depicted in Fig. 2. The horizontal lines denote the Fermi energies of the Cr and labeled alloys. According to the rigid band approximation the addition of 10 and 20 atomic % V to Cr causes the Fermi energy to decrease and changes the Fermi surface topology. The concentration dependences of the alloy topologies are shown in Fig. 3. As shown in this figure, when lowering the Fermi energy, the *lens* shrinks rapidly, while the *ellipse* expands modestly and the *octahedron* and *nesting* contract modestly. Hence, the period would be expected to grow dramatically if it is controlled by the lens, grow only modestly if due to octahedral spanning vectors or aliasing of the nesting vector, but only to shrink incrementally if controlled by the *N*-centered *ellipse*. From the experimental result of observing a slight decrease of the period for each crystalline orientation

with increasing V addition, we conclude that the long-period oscillation of Cr originates from the ellipse caliper, as argued by Stiles[9] and Tsetseris *et al.*[10]

V. CONCLUSIONS

The period of the oscillatory exchange coupling of $Fe/Cr_{1-x}V_x$ [x = 0.085, 0.21] (100) and (211) superlattices was studied in order to understand the origin of the 18-Å 'long' period of the Fe/Cr system. Epitaxial $Fe/Cr_{1-x}V_x$ (100) and (211) superlattices were grown on MgO (100) and (110) substrates, respectively, by dc magnetron sputtering, and the dependence of the magnetoresistance as a function of spacer layer thickness was measured at room temperature. The periods are found to slightly decrease with V addition, such that it becomes ~16 Å (x = 0.085) and ~15 Å (x = 0.20) for $Fe/Cr_{1-x}V_x$ (211), and ~17 Å (x = 0.085) and ~16 Å (x = 0.20) for $Fe/Cr_{1-x}V_x$ (211). With these experimental results in hand and giving consideration to the theoretically anticipated evolution of the Fermi surface topology with V alloying within the rigid band picture, we can conclude that the long period is due to the caliper vector of the *ellipse* centered at the *N* point of the Fermi surface.

ACKNOWLEDGMENTS

Work supported by the U.S. Department of Energy, BES-Material Science, under Contract No. W-31-109-ENG-38. And one author (CYY) wishes to acknowledge the financial support of the Korea Research Foundation made in the program Year 1997.

Figure Captions

Fig. 1 The spacer-layer thickness dependence of the magnetoresistance for (100)- and (211)-oriented Fe(14 Å)/$Cr_{1-x}V_x$ (t_{spacer}) superlattices measured at room temperature. (a) x = 0.085 and (b) x = 0.2 for the (100) orientation, and (c) x = 0.085 and (d) x = 0.2 for the (211).

Fig. 2 The band structure of Cr group transition metals based on the tight binding method. The Fermi energy for each composition is indicated as is the lens and ellipse.

Fig. 3 Fermi surfaces of bulk Cr (thick curves), $Cr_{1-x}V_x$, x = 0.1, 0.2 (thin, thinner), showing cuts across the ellipse, lens and nesting region, from top to bottom, respectively. The arrows indicate the direction from a Cr-rich to a more V-rich alloy. The Fermi surfaces were generated by the linearized augmented-plane-wave method with bulk parameters.

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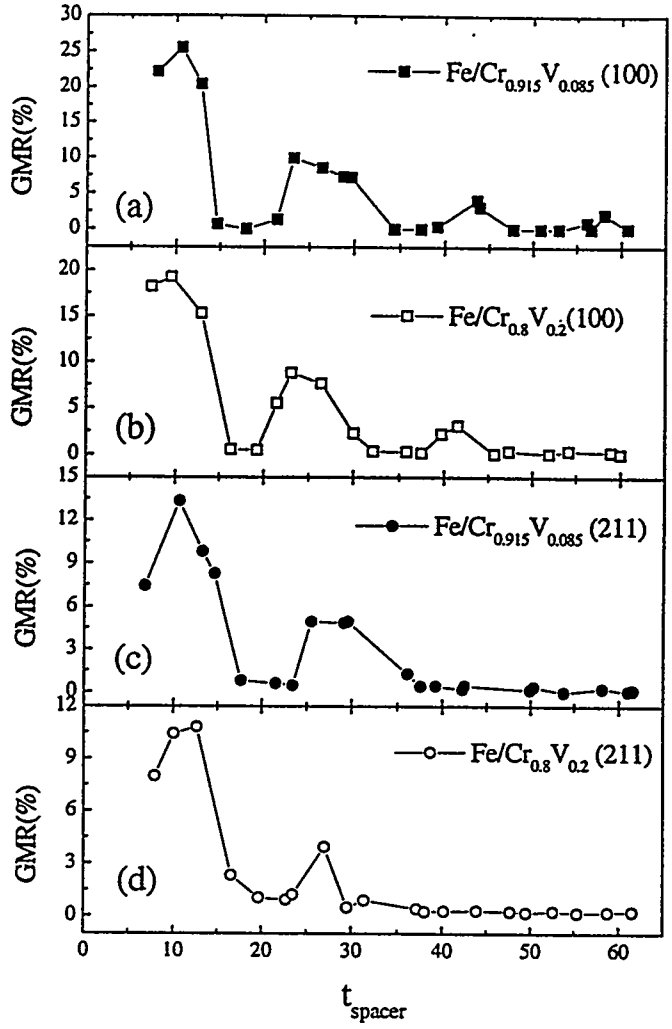
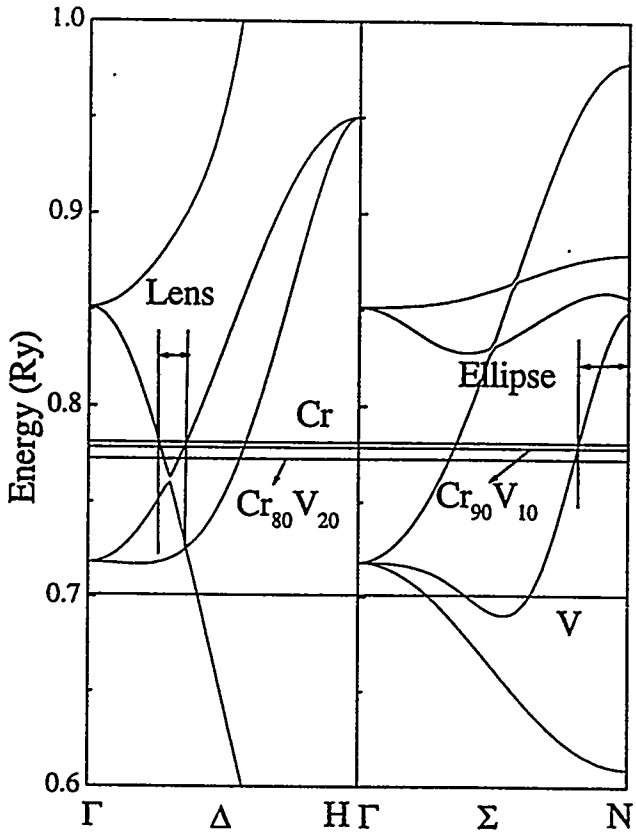
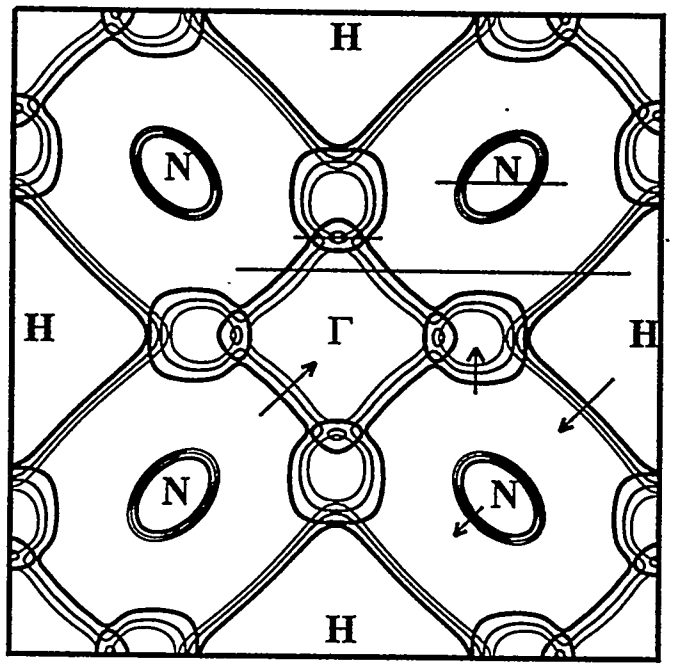


You et. al JAP, Fig. 1



You et. al JAP, Fig. 2

Cr[thick] vs alloys[thick]



You et. al JAP, Fig. 3