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MAGNETORESISTANCE OF EPITAXIALLY GROWN METALLIC MULTILAYERS

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ABSTRACT

The epitaxial TM/bcc-Cr(001) (TM=Fe, Co, Ni) multilayers have been prepared using MBE. The crystal structure, interlayer exchange coupling and magnetoresistance of those multilayers have been discussed. The structure of Fe, Co and Ni grown on bcc-Cr(001) exhibited bcc(001), distorted hcp(11$\bar{2}$0) and fcc(110), respectively. In Fe/Cr multilayes, an oscillatory exchange coupling has been observed, but not observed in Ni/Cr system, which may come from the large mixing at interfaces. Large MR ratio (116%, 4.2K) has been obtained in Fe/Cr system, but only 2% in Co/Cr system. This difference can be understood from the view point of the relative potential geight for down spin electrons between TM and Cr.

INTROCUCTION

The oscillatory ecchange coupling[1] and associated giant magnetoresistance (GMR) effect[2] in magnetic multilayers are currently of great interest. Since the discovery, much work has been carried out on these phenomina in various kinds of multilayers. Recently, a maximum magnetores-istanec (MR) ratio of 220%(1.5K) has been found in high-quality epitacially grown Fe/Cr(001) multilayers[3]. Since both the antiferromagn-etic (AF) coupling and the magnetoresistance are very sensitive to the structural quality of multilayers, high zuality samples and detailed structural investigation are necessary to understand these phenomena. The crystal structure of Fe and Cr are the same body-centered-cubic (bcc), and lattice mismatch is very small, which is adbantage to prepare good samples. On the other hand, those of Co and Ni in the bulk state are hexagonal-closed packed(hcp) and face centered cubic(fcc) structure, therefore their lattice matchings to Cr are not good and well controlled epitaxeal sample preparation is very diffcult. Although it is interesting to know the exchange coupling and the MR effect of the epitaxial [Co/Cr] and [Ni/Cr] multil-ayers, little studies have been reported so far, for these reasons. The MR of the [Co/Cr] multilayer was first measured by Parkin et al.[1], however the film structure was not reported in detail. The preparation of the epitaxial [Co/Cr] multilayers were reported by Th.Zeidler et al[4], but the MR measurement was not performed because of thick buffer layers. In the [Ni/Cr] case no study of epitaxial multilayers has been reported so far.

In this paper we present the magnetization and MR effect measurements of TM/bcc-Cr (001)(TM=Fe, Co, Ni) multilayers prepared carefully by molecular beam epitaxy (MBE) technique, and compare those properties to each other.

EXPERIMENTAL PROCEDURE

Samples were grown on MgO(001) substrates in an ultrahigh vacuum chamber (VG Semicon V80M system) with a base pressure of 1×10^{-11} Torr. The Fe, Co and Ni layers were deposited by eb-guns and Cr is using Knudsen cell with a rate of 3-5Å/min. The 50-100Å Cr buffer layers were deposited onto the substrate, and followed by $[TM/Cr]_{20}$ multil-ayers. The substate temperature was held at 500℃ during the buffer deposition, and down to 90℃. the surface structure of the films was examined by reflection hegh-energy-electron diffraction (RHEED) observations during the growth. The stucture of multilayers perpendicular to the film plane was determined by X-ray diffraction using CuK$_\alpha$ radiation. Magnetization measurements were carried out by vibrating sample magnetometor (VSM) and superconducting quantum interference device (SQUID) magnetometry. In the case of the [Co/Cr], which shows the perpendicular anesotropy, magnetic field was applied both in the plane of the sample and perpendecular to it. The MR effect was measured by the conventional four point method. A superconducting magnet (10T) was used for the [Fe/Cr] because of the large saturation magnetic field. In this study, the MR ratio is defined as $(\rho_0-\rho_s)/\rho_s$, where ρ_0 is the resistivity at H=0kOe and ρ_s is at the saturation field Hs.

RESULTS AND DESCUSSION

Fig. 1 shows the typecal high angle X-ray diffraction patterns of [TM/Cr] on bcc-Cr (001) multilayers. Several satellite peaks in the pattern indicate the ebidence for the good artificial periodic structure. The large intensity of satellite peaks in [Co/Cr] and [Ni/Cr] suggest that there is a difference between the interlayer spacing of TM(=Co, Ni) and Cr. According to the analysis of them[5] using step model as shown in Fig. 2, the lattice spacing of Fe and Cr perpendicular to the film plane are almost the same as bulk values of $d_{(002)}$. On the countary, those of Co and Ni are small compared to Cr, and reduced asympt-otically to $d_{(1120)}$ of bulk hcp-Co and $d_{(220)}$ of fcc-Ni as the Co or Ni thickness is thicker. These results indicate that the crysal

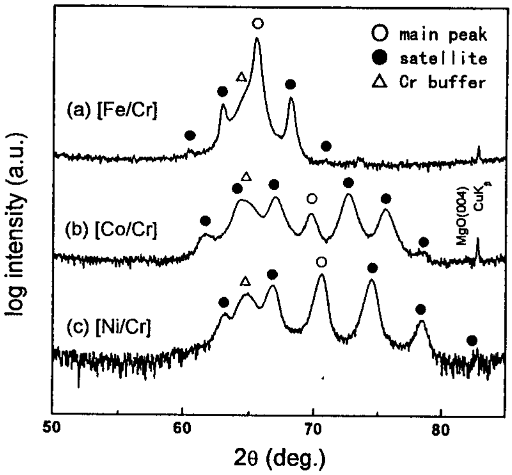

Fig. 1 High angle X-ray diffraction patterns of [TM/bcc-Cr(001)] (TM=Fe, Co, Ni) multilayers. (a) $[Fe20Å/Cr20Å]_{20}$. (b) $[Co20Å/Cr18Å]_{20}$. (c) $[Ni16Å/Cr12]_{20}$.

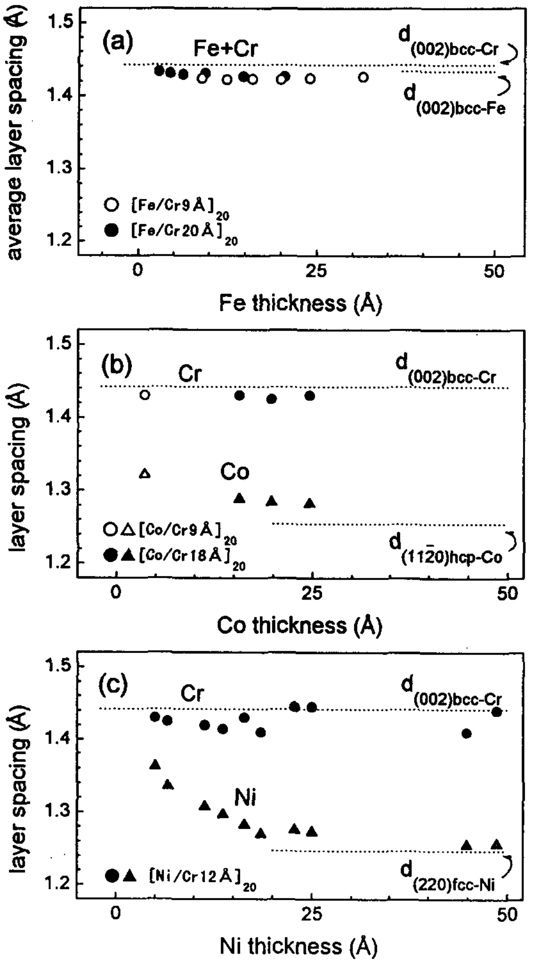

Fig. 2 Variations of layer spacing of TM and Cr in [TM/bcc-Cr(001)] (TM=Fe,Co,Ni) multilayers as a function of TM layer thickness. (a)[Fe/Cr]. In[Fe/Cr] (b)[Co/Cr]. (c)[Ni/Cr], the average layer spacing of Fe and Cr is plotted since it is difficult to separete similar layer spacings.

stucture of Fe and Cr in [Fe/Cr] multilayers are bcc, however Co and Ni are distorted hcp $(11\bar{2}0)$ and fcc(110) respecti-vely. Details are described elsewhere together with the analysis of RHEED observations[5].

Fig. 3 shows the magnetization curves of [TM/Cr] multilayers. The mesured saturation magnetization(Ms) of Fe in [Fe/Cr] is almost the same to the bulk value, however that of Co and Ni in multilayers are much reduced from bulk values (Ms of the bulk bcc-Fe, hcp-Co and fcc-Niare 221.9, 162.5 and 57.5 emu/g respectively at 0K). It suggests the possibility of the formation of CoCr and NiCr alloys lauer at interfaces of multilayer, which is discussed in later.

The hysteresis loop of [Co8Å/Cr20Å]$_{20}$ indicates that the 8Å Co layer on Cr has the perpendicular anisotropy and that the Co layers are ferromagnetically coupled the large remanent magnetization is observed. By varying Cr thickness, loop shapes are drasticallu changed. The hysteresis loop of [Co8Å/Cr9Å]$_{20}$ has on remanent magnetization and the spin flop transition is observed at approximately 9kOe. As calculated the similar type of the spin flop in the bilauer film[6], the magnetization of Co layers in [Co8Å/Cr9Å]$_{20}$ are antiferromagnetically coupled through the Cr layer and oriented perpendicular to the film plane, at zere field.

As described above, the interlauer exchange coupling could be evaluated by the remanent magnetization (Mr). In Fig. 4, the magnitude of Mr/Ms was plotted for [TM/Cr] multilauers as a function of Cr lauer thickness. The data for the [FE/Cr] multilayers are quoted from those obtained by E.E. Fullerton et al[7] as plotted in Fig. 4b.

As shown in Fig. 4a, an oscillatory Cr thickness dependence of Mr/Ms was observed for the [Co/Cr] multilauers, which is almost the same as the [Fe/Cr] multilauers (Fig. 4b). On the other hand, the magnitude of Mr/Ms of the [Ni/Cr] multilayers is relatively high, and has no Cr thickness dependence,

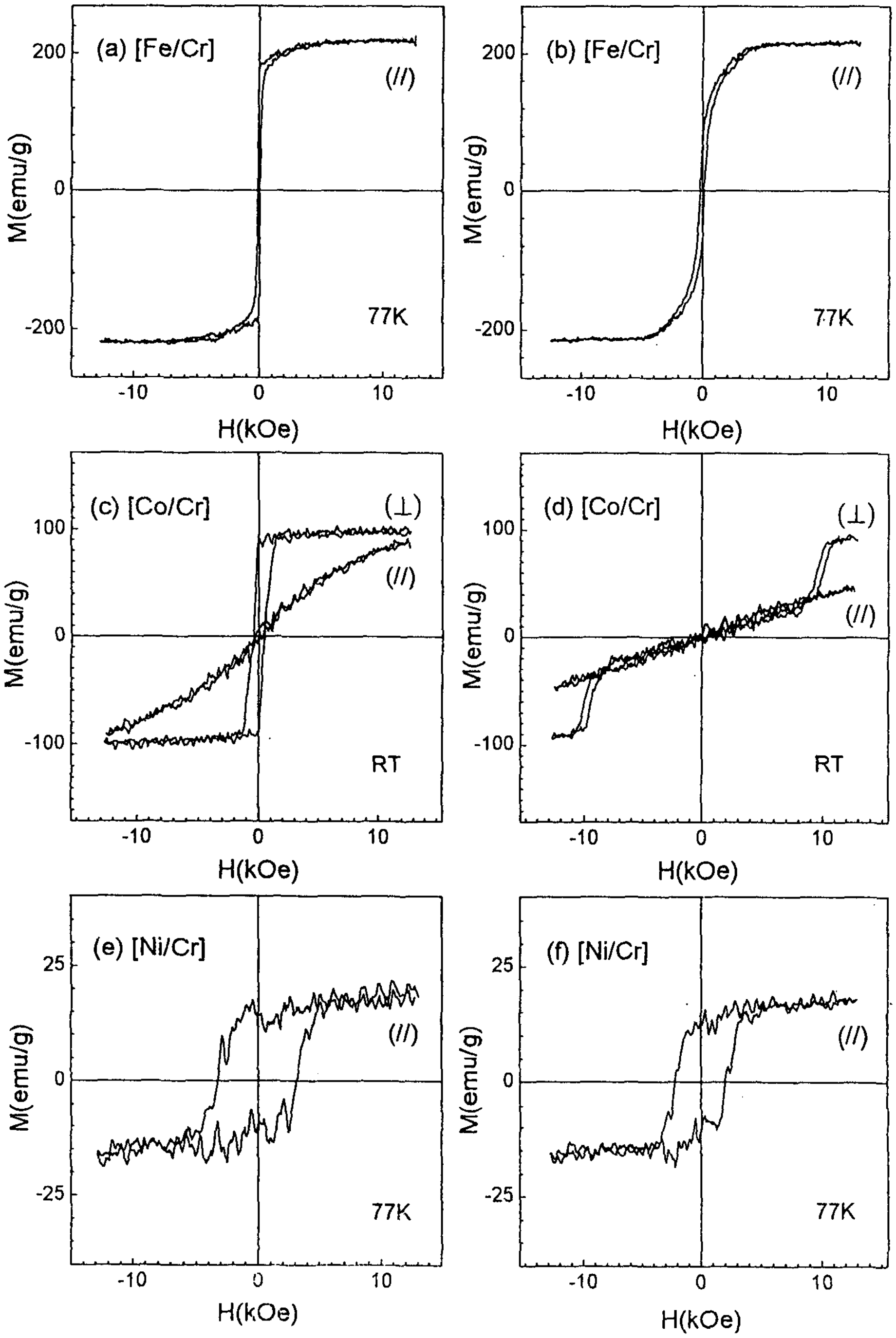

Fig. 3 Magnetization curves of [TM/bcc-Cr(001)] (TM=Fe, Co, Ni) multilayers. (a) [FeÅ/Cr20Å]$_{20}$. (b)[Fe20Å/Cr13Å]$_{20}$. (c) [Co8Å/Cr18Å]$_{20}$. (d) [Co8Å/Cr9Å]$_{20}$. (e) [Ni18Å/Cr22Å]$_{20}$. (f) [Ni18Å/Cr12Å]$_{20}$. (//): a magnetic field was applied in the film plane. (⊥): perpendicular to the film plane.

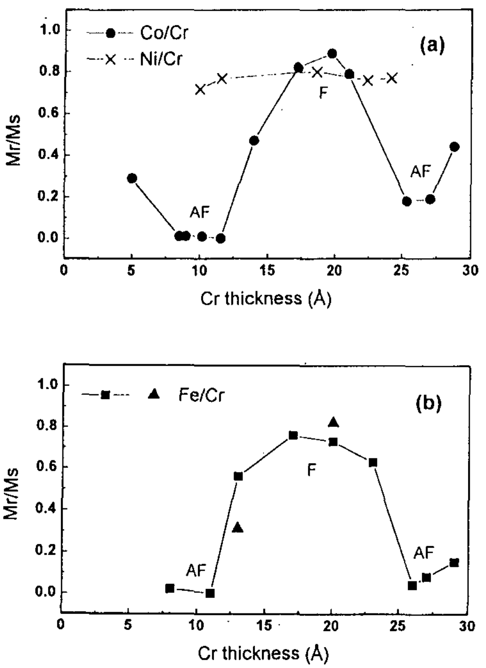

Fig. 4 Variations of Mr/Ms of [tM/bcc-Cr(001)] (TM=Fe, Co, Ni) multilayers as a function of Cr theckness. (a)[Co8Å/Cr]$_{20}$ at RT and [Ni18Å/Cr]$_{20}$ at 77K. (b)circle:rif.7, triangle: prescnt data of [Fe20Å/Cr]$_{20}$ at 77K.

which indicate the ferromagnetic or magnetically uncoupled state between Ni layers. In order to explain the disapperance of AF coupling in the [Ni/Cr], differences of spacer layer are considered from the view point of mixing of Ni and Cr at interfaces, as follows.

In order to evaluate the thickness of the interlayer mixing. the following approximations were adopted.

1) The compositional profile is asuumed to be trapexoedal.

2) The magnetization of the pure Co (or Ni) lauer is taken to be the bulk hcp-Co valuem Ms.$_{hcp-Co}$ (or fcc-Ni, Ms.$_{fcc-Ni}$).

3) The magnetization of the mixing region is taken to be the same compositional dependence as bulk magnetization, where the bulk CoCr and NiCr allous become nonmagnetic at 25% at.Cr and 12% at.Cr respectively.

According to these assumptions, a schematic representation of the TM (Co, Ni) concentration and magnetization profiles along the growth direction is given in Fig. 5, where $t_{Co(or\ Ni)}$ and t_{mix} denote the thickness of Co (or Ni) effective lauers and that of mixing region, respectively. Using thes model, the measured magnetizations satisfy the following expressions.

$$Ms\ t_{Co}=Ms._{hcp-Co}\ (t_{Co}-0.75t_{mix}):for[Co/Cr] \quad (1)$$

$$Ms\ t_{Ni}=Ms._{fcc-Ni}\ (t_{Ni}-0.88t_{mix}mix):for[Ni/Cr] \quad (2)$$

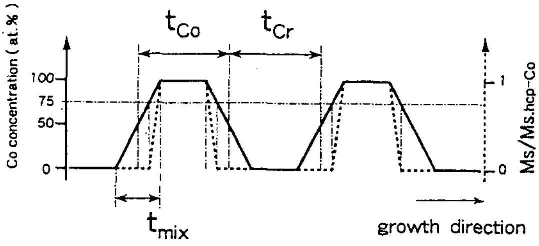

Fig. 5 schematic representation of the TM(Co,Ni) concintration and magnetization profiles along the growth diection.

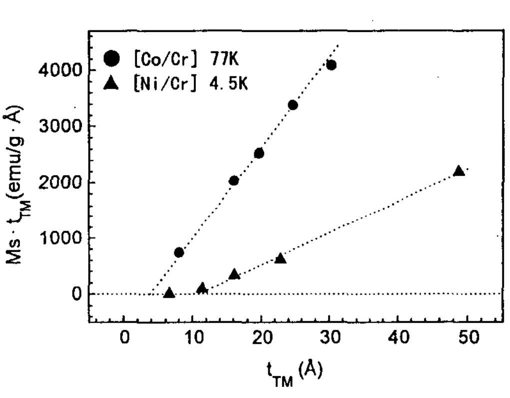

Fig. 6 Ms-t_{TM} as a function of the effective layer theckness, t_{TM}(TM=Co, Ni).

The experimental results of $Ms \cdot t_{TM}$ as a function of the effecitive layer thickness, t_{TM} (TM=Co, Ni) are shown in Fig. 6. As a results of the analusis, tmix of about 5Å for [Co/Cr] and about 12Å for [Ni/Cr] were obtained.

In the [Ni/Cr] multilayer, the large interlayer mixing might reduce the AF coupling between Ni layers. As an another reason, we perpose that the existence of the different two kinds of materials (Cr and NiCr) in a spacer layer causes the discontinuity of the reciper-ocla bectors which contribute to the interlayer exchange coupling.

Fig. 7 shows the MR curves of [TM/Cr] multilayers. The maximum MR ratio of the [Fe/Cr] multilayers is 116% at 4.2K, however that of the [Co/Cr] is 2% at most. This dif-erence can be understood by the calculated results obtained by Inoue et al[8]. According to their model, the cinduction electrons are scat-tered by the spin dependent random exchange potential, which is defined as the impurity potential caused by the random substitution of atoms at the interface. As a results of their calculation, a later MRratio is obtained for the [Fe/Cr] multilayer since the difference between the potential of down spin conduction electron in Fe and Cr, $\Delta\varepsilon$(Fe/Cr), is nearly equal, and the resistibity of down spin electrons is much reduced at the ferromagnetically coupled configuration of Fe layers. In the case of the [Co/Cr] multilayerm $\Delta\varepsilon$(Co/Cr) is larger than $\Delta\varepsilon$(Fe/Cr) and the MR ratio becomes small. It is difficult for the quantitatibe comparison of our experimental results with the model. However, a large difference of the MF ratio between [Fe/Cr] and [Co/Cr] found in our

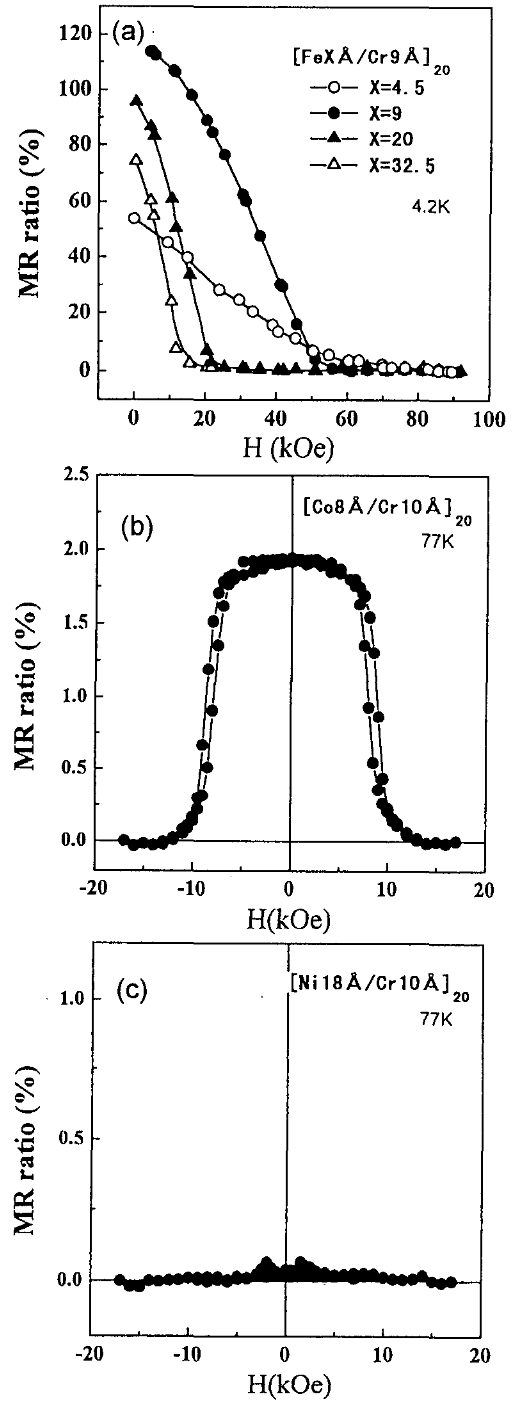

Fig. 7 MR curves of [TM/bcc-Cr(001)] (TM=Fe, Co, Ni)multilayers.

works is qualitatively consistent with the calculated results. The MR ratio of the [Ni/Cr] multilayers is much small (about 0.1%), which is explained by nin AF coupling between Ni layers.

CONCLUSIONS

The epitaxial $[\mathrm{TM/bcc\text{-}Cr(001)}]_{20}$ (TM= Fe,Co,Ni) multilayers were prepared using MBE methods. The crystal structure of Fe, Co and Ni grown on the bcc-Cr(001) were bcc(001), distorted hcp($11\bar{2}0$) and distorted fcc(110) respectibely. The oscillatory behavior of the interlayer exchange coupling was found in [Fe/Cr] and [Co/Cr], but no oscillatory behavior in [Ni/Cr]. By means of an analysis of the saturation mgnetizationm a thickness of the mixing layer was evaluated. The MR ratio of 116% for [Fe/Cr] and 2% for [Co/Cr] were obtained, which is explained by Inoue's calculation. The MR ratio of [Ni/Cr] was 0.1% at most because of a large interlayer mixing of [Ni/Cr].

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