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Giant magnetoresistance of Fe/Cu/Fe(001) trilayers grown directly on GaAs(001)

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The giant magnetoresistance of crystalline Fe/Cu/Fe(001) epitaxial structures characterized by scanning tunneling microscopy are presented. Fe/Cu/Fe(001) trilayers capped with Au are grown directly on GaAs(001) using a new procedure for producing pure Fe layers with As-free Fe surfaces on GaAs(001). The temperature dependence of the magnetoconductance and sheet resistance measured from 4 to 300 K is modeled by the Boltzmann equation assuming that the mean free paths in the crystalline epitaxial layers are equal to those in bulk materials. The results of the simple model suggest that the coefficient of the specular scattering at the Fe/GaAs interface is $R=0.45$, while the scattering at the outer Au interface is diffuse. Spin asymmetry scattering at the metallic interfaces is $\Delta T=|T^{\uparrow}-T^{\downarrow}|=0.34$, $T^{\text{avg}}=(T^{\uparrow}+T^{\downarrow})/2=0.79$. The sheet resistance was best modeled using a low temperature mean free path of 25 nm in the Fe layer. *© 2000 American Institute of Physics.* [S0021-8979(00)71708-7]

The purpose of the study is to characterize the interface topography and investigate the GMR of high quality Fe/Cu/Fe(001) trilayers deposited on As-free Fe directly grown on (4×6)-GaAs(001). The GaAs surface was prepared by inserting an epiready American Xtal Technology wafer in UHV without prior treatment and annealing to roughly 500 °C to desorb the carbon from the substrate. The oxide was removed by 500 eV Ar^{+} sputtering at an angle of 75° with respect to the surface normal. Substrates prepared at Simon Fraser University (SFU) were rotated about their normal during sputtering, whereas the apparatus at the Max Planck Institut (MPI) did not allow sample rotation during sputtering. The sputtering was performed at room temperature under Auger observation until the contaminants were removed. The sample temperature was gradually raised under reflection high-energy electron diffraction (RHEED) observation until a well ordered (4×6) reconstruction was obtained at a temperature of roughly 600 °C. See Ref. 1 for further details.

STM studies presented in this article, see Fig. 1, show that the GaAs surface has a pseudo (4×6) reconstruction, which is a combination of (4×2) domains and (1×6) domains.[2] The relative area occupied by each domain depends on the temperature. The (1×6) reconstruction is a more As rich surface than the (4×2) and, hence, is more volatile. As the temperature is increased the (4×2) domains increase as the As is evaporated from the (1×6) reconstruction. Terraces are typically 400 Å wide. The rms roughness, σ, for a (4×2) terrace is 0.3 Å, and 0.7 Å for a (1×6) terrace.

Fe was grown by thermal deposition at a rate of 1 Å/min as determined by a quartz crystal monitor. The RHEED beam was set to the first anti-Bragg condition for Fe, at a polar angle of approximately 1° glancing incidence, and an azimuthal angle 0.8° away from the 1–10 direction. The sample rotation during sputtering proved to be an important step. The Fe grown on GaAs(001) showed RHEED oscillations only when the substrate was prepared in this fashion. RHEED patterns before and after growth were, however, qualitatively the same for samples with or without rotation during sputtering. STM images of a GaAs terrace covered by

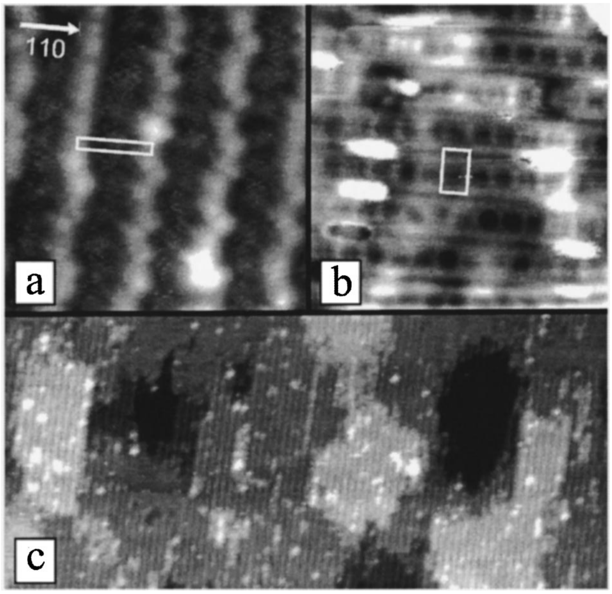

FIG. 1. Filled state STM images of pseudo (4×6) GaAs(001) with 0.3 nA tunneling current and -1.80 V bias voltage. (a) $100\times100\ \text{Å}^2$ image of a (1×6) domain with a vertical rms roughness $\sigma=0.7$ Å. The size of the (1×6) unit cell is shown by the white box. The crystal orientation labeled in the top right hand corner is the same for all three images. (b) $100\times100\ \text{Å}^2$ image of a (4×2) domain where $\sigma=0.3$ Å. A white box shows the size of the (4×2) unit cell. (c) 770×2000 Å image of pseudo (4×6) GaAs(001), $\sigma=2.1$ Å.

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Fe indicated that the σ of the Fe surface increased from 1.2 Å at a thickness of 1.4 ML to 1.9 Å at 20 ML. The average lateral size of the Fe terraces increased from 14 to 45 Å in the same thickness range indicating that the characteristic angle for surface roughness was changing from 17° to 10° with increasing Fe thickness.

The chemical evolution of the Fe film was monitored by x-ray photoelectron spectroscopy (XPS). There was As segregation to the Fe surface. After deposition of 20 ML of Fe/GaAs(001), the films were sputtered with 500 eV Ar^+ at an angle of 75° with respect to the surface normal until the As $2p_{3/2}$ line disappeared. The samples prepared at SFU were rotated during sputtering whereas samples prepared at MPI for STM studies were sputtered only at a fixed angle. In the process of cleaning the surface, 2.2 ML of Fe was removed as determined from the decrease in the intensity of the Fe $2p_{3/2}$ peak. From the Ga $2p_{3/2}$ line, it was found that roughly 0.2–0.3 ML of Ga was released into the Fe layer as a result of cascade mixing from the sputtering.

The Fe films can be annealed to 200 °C without any further intermixing, contrary to the case where Fe is initially deposited at elevated temperatures which results in alloying at the Fe/GaAs interface.[3] In order to repair the damage created by sputtering, additional Fe layers were further deposited at a temperature of 200 °C. In the case of samples prepared at SFU (using rotation while sputtering As away), the RHEED intensity increased by a factor of three over the course of a 10 ML Fe deposition and strong RHEED intensity oscillations were recovered. Samples prepared at MPI led to a small or no increase in RHEED intensity and no RHEED oscillations were observed. In both cases the growth at increased temperatures created narrow RHEED streaks indicating an increase in terrace size.

The roughness of the Fe film was strongly dependent on the substrate temperature, T_{sub}, during the growth. At $T_{\mathrm{sub}} \sim 150\,^{\circ}\mathrm{C}$, σ decreased to 1.4 Å and the lateral terrace size increased to 90 Å, see Fig. 2(a). At $T_{\mathrm{sub}} \sim 170\,^{\circ}\mathrm{C}$ $\sigma = 2.4$ Å and the lateral terrace size rose to 180 Å. The characteristic roughness angle decreased monotonically from 8.7° to 3.0° for T_{sub} from 20 to 170 °C.

Cu adatoms have a high mobility at RT and consequently it was difficult to grow Cu on Fe(001) due to its tendency to form nanocrystallites. However, by cooling to temperatures below 190 K, the mobility of the Cu is reduced to the point where the system grows in a quasilayer by layer mode as indicated by the presence of RHEED oscillations which persist up to 13 ML of bcc Cu. This behavior was observed for samples grown at SFU and MPI. After the growth of roughly 10 ML of Cu, a lattice reconstruction was visible in the RHEED patterns. 13 ML Cu/28 ML Fe/GaAs(001) sample was imaged with STM showing that the reconstruction consisted of corrugations along either the [010] or [100] directions with a periodicity of (12.1 ± 1.8) Å and with a small vertical height variation of 0.3 Å, see Fig. 2(b). The average island separation was 100 Å and $\sigma = 1.5$ Å.

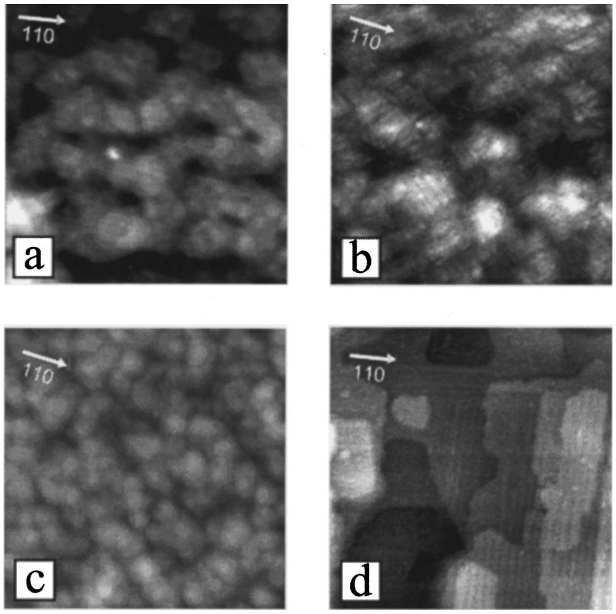

FIG. 2. 500×500 Å^2 STM images of the metallic interfaces in the Au/Fe/Cu/Fe/GaAs(001) trilayer structures. The crystal orientation indicated in the top left corner in each figure corresponds to the orientation of GaAs substrate. (a) STM image of 10 ML of Fe grown at $T_{\mathrm{sub}} = 423$ K on As-free Fe/GaAs(001), $\sigma = 1.4$ Å, (b) 13 ML Cu grown at $T_{\mathrm{sub}} = 190$ K on 28 ML Fe/GaAs(001), $\sigma = 1.4$ Å, (c) 10 ML Fe grown at RT on Cu/Fe/GaAs(001), $\sigma = 1.8$ Å, and (d) 5×1 reconstruction of 20 ML Au on Cu/Fe/GaAs(001), $\sigma = 1.1$ Å.

Ferromagnetic resonance studies have shown that Fe layers prepared at SFU have their magnetic properties well described by interface and bulk contributions.[1] MOKE and magnetoresistance were performed on 20 ML Au/10 ML Fe/XCu/28 ML Fe/GaAs(001) trilayers, where X ($X = 9, 11, 13.2$) is the number of Cu atomic layers. The samples were patterned *ex situ* in order to measure MOKE and magnetoresistance in a four-probe geometry simultaneously. Both the samples with 9 and 11 ML Cu spacers were ferromagnetically coupled. Only the samples with a 13.2 ML Cu spacer showed noncollinear coupling for small applied magnetic fields, and were used for GMR studies.

The resistance of the sample was measured over an area of $1.2 \times 0.5\,\mathrm{mm}^2$. At saturation the resistance measured at 300 K was 25.83 Ω for current perpendicular to the applied magnetic field and dropped to 16.35 Ω at 4 K. A typical magnetoresistance measurement is shown in Fig. 3(a), where regions of antiparallel, noncollinear, and parallel configurations of the magnetic moments of the two films are clearly visible. The GMR ratio increased from 2.0% to 5.5% as the temperature was dropped from RT to 4 K. Compared to bulk measurements the temperature dependence of the resistance was weak, as shown in Fig. 3(b), suggesting that the electron transport is strongly affected by diffuse scattering at both the outer Au surface and the Fe/GaAs interface. The measured resistance was compared to that expected from the solution of the Boltzmann equation as outlined in Ref. 4. The mean free paths for Fe, Cu, and Au and their temperature dependence in crystalline epitaxial structures were assumed to be equal to those in bulk materials. The mean free paths for Fe, Au, and Cu were determined from bulk resistivity measurements[5] using a simple formula for the conductivity, $\sigma = (2me^2/3\pi^2\hbar^3)E_F\lambda$, where m is the electron mass, e is the electron charge, E_F is the Fermi energy, and λ is the

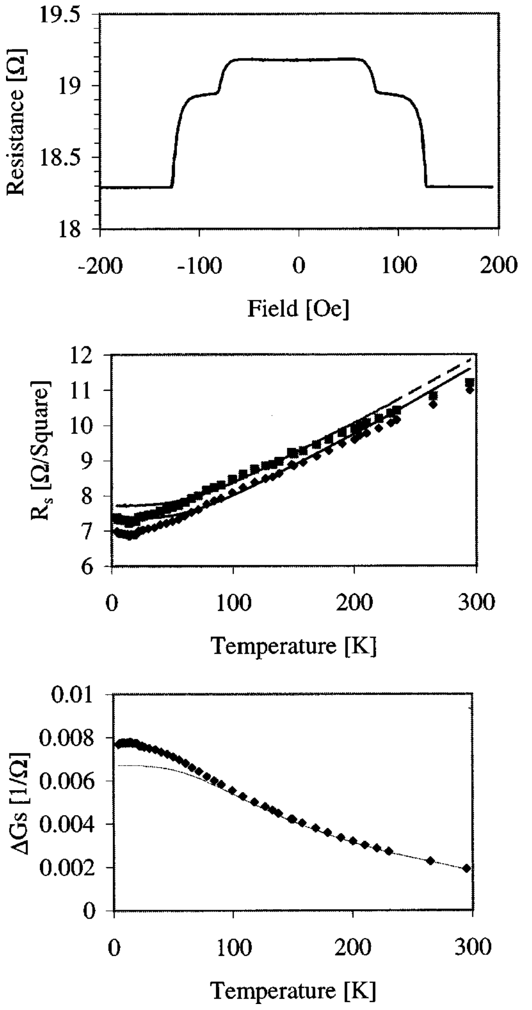

FIG. 3. Magnetotransport measurements of 20 Au/10 Fe/13.2 Cu/28 Fe/GaAs(001). (a) The magnetoresistance at 83 K for the current perpendicular to the applied field direction. The hysteresis was removed by a 100 Oe transverse ac field for each applied dc field as described in Ref. 1. (b) The temperature dependence of the sheet resistance (◆), (■) and the calculated sheet resistance (solid line, dashed line) at saturation and zero applied field respectively. (c) The temperature dependence of the change in sheet magnetoconductance ΔG, where the solid line is the calculated ΔG given by the parameters explained.

mean free path. The mean free paths and resistance ratios at RT for Fe, Au, and Cu are 9.3 nm(430), 32 nm(100), and 42 nm(840), respectively, where the number in brackets represents the resistance ratio $R(293\,\mathrm{K})/R(10\,\mathrm{K})$. In Fe, the ratio of mean free paths for majority to minority electrons is ~ 0.7,[6] while the spin asymmetry scattering is expected to be approximately 10 for Fe/Cu.[7] This led us to compare our magnetoconductance studies with calculations based on interface spin dependent scattering. The change in magnetoconductance ΔG is defined in the usual manner as the difference in sheet conductance between parallel and antiparallel orientations of the magnetic moments in the two Fe layers. Assuming complete diffuse scattering at the outer interfaces, the temperature dependence of ΔG was much less than that observed.

A better fit can be obtained by assuming a partial reflectance of electrons at least at one of the outer interfaces. An estimate of the specular scattering can be obtained from the parameter describing the effective angle of sloping interface facets, $4\pi\sigma/L$, and L is the average terrace size.[8] Using our STM data, this parameter is 0.002 in the case of GaAs/Fe interface, see Fig. 1, and ranges between 0.1 and 0.5 at the metal–metal and the outer Au interfaces, see Figs. 2(a)–2(d). For that reason partial specular scattering was assumed only at the Fe/GaAs interface. The fit of the temperature dependence of ΔG could be further improved by including a realistic mean free path of 25 nm in the Fe film due to defect scattering, $1/\lambda_{\mathrm{Fe}}^{\mathrm{film}} = 1/25\,\mathrm{nm} + 1/\lambda_{\mathrm{Fe}}^{\mathrm{bulk}}$, yielding a resistance ratio of 3.6. This additional scattering may be due to the presence of a small concentration of Ga in the thick Fe film, as measured by XPS, see earlier.

Fitting of the magnetoconductance and the sheet resistance was carried out using the following assumptions: (1) the reflection coefficients, R, at the Fe/GaAs interface are spin independent, (2) the Fe/Cu and Fe/Au interfaces have the same spin dependent transmission coefficients $T^{\uparrow}, T^{\downarrow}$ and have $R=0$, and (3) the scattering at the outer Au interface is purely diffuse. The best fits were obtained for $\Delta T = |T^{\uparrow} - T^{\downarrow}| = 0.34$, $T^{\mathrm{avg}} = (T^{\uparrow} + T^{\downarrow})/2 = 0.79$, and $R^{\mathrm{Fe/GaAs}} = 0.45$. Using these values, good overall fits are obtained above 80 K for the magnetoconductance ΔG, see Fig. 3. ΔG was more strongly affected by ΔT than by T^{avg}. Disagreement between the fit and experiment at low temperatures can be improved by assuming that ΔT gradually increases by 0.02 from 80 to 4 K. This could imply that spin mixing somewhat affects the electron transport through the metallic interfaces. The spin asymmetry scattering is significantly smaller than the spin asymmetry ratio implied by calculations for Cu impurities in an Fe host.[7] Therefore, one should not *a priori* exclude a bulk contribution to ΔG. The relative bulk and interface contributions will be unambiguously separated by a series of samples with a variable Fe layer thickness.

$T^{\mathrm{avg}} = 0.79$ was chosen to obtain a good fit of the sheet resistance in the intermediate temperature range. The fit of the sheet resistance differs at both low and high temperature regions. Below 80 K the fit can be improved by increasing T^{avg} to 0.83 implying that the electron transmission coefficients are affected by soft interface phonon modes. However, the deviation of the fit above 180 K, see Fig. 3, is not easy to improve within our existing assumptions. Further studies using samples with variable thickness of the individual layers are needed to refine the theoretical modeling.

[1] T. L. Monchesky, B. Heinrich, R. Urban, K. Myrtle, M. Klaua, and J. Kirschner, Phys. Rev. B **60**, 10242 (1999).
[2] Q. Xue, T. Hashizume, H. M. Zhou, T. Sakata, T. Ohno, and T. Sakurai, Phys. Rev. Lett. **76**, 3177 (1995).
[3] A. Filipe, A. Schuhl, and P. Galter, Appl. Phys. Lett. **70**, 129 (1997).
[4] H. J. M. Swagten, M. M. H. Willekens, and W. J. M. De Jonge, in *Frontiers in Magnetism of Reduced Dimension Systems*, NATO-ASI, Series B3: High Technology, Vol. 49 edited by V. G. Bar'yakhtar, P. E. Wigen, and N. A. Lesnik (Kluwer Academic, Dordrecht, 1998), p. 471.
[5] *CRC Handbook of Chemistry and Physics*, edited by D. R. Lide (CRC, Boca Raton, 1999).
[6] B. A. Gurney, V. S. Speriosu, J.-P. Nozières, H. Lefakis, D. R. Wilhoit, and O. U. Need, Phys. Rev. Lett. **24**, 4023 (1993).
[7] I. Mertig, Rep. Prog. Phys. **62**, 237 (1999).
[8] J. M. Ziman, *Electrons and Phonons* (Oxford University Press, Oxford, 1960), p. 458.