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MAGNETIC-PROPERTY CHANGES IN EPITAXIAL METAL-FILM SANDWICHES*

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Magnetic-Property Changes in Epitaxial Metal-Film Sandwiches*
Running Title: Property Changes in Metal-Film Sandwiches

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ABSTRACT

Epitaxial metal film sandwiches (EMFS) containing Pd or Cr, have been prepared between single-crystal Ag or Au. The modified Pd/Cr show major changes in physical properties. Pd has a stretched lattice parameter in Au-Pd-Au, which combines with a tetragonal distortion to cause exchange enhancements up to 28000 and spin-fluctuation temperatures of 1-10 K. In Au-Cr-Au, Cr takes up the fcc structure, leading to superconductivity due to a high $N(E_F)$. These results are contrasted to data for Ag-Pd-Ag and Ag-Cr-Ag EMFS.

1. INTRODUCTION

This paper reviews recent work with thin film metal sandwiches of the type A-B-A where A = Au or Ag and B = Pd or Cr. It has been found that when A and B form the same structure but have a different lattice parameter, a_0 , the stretching of the smaller lattice can lead to new magnetic phenomena when the stretched atom is already nearly magnetic, as for Pd. Similarly, when the bulk atomic arrangements are different but there is a strong epitaxial relationship between the metals A and B, the atoms of metal B may take up the structure of A. This seems to be the result for Au-Cr-Au, where the Cr now forms in the fcc structure leading to a major change in its magnetic properties. Earlier accounts of this work and experimental details may be found elsewhere [1-3].

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The near-magnetism of Pd and effects of spin fluctuations are well-known [4]. At temperatures above ≈ 150 K, the susceptibility, χ , follows a Curie-Weiss law, $\chi = C/(T - \Theta_{CW})$ with $\Theta_{CW} = -260$ K. However, at lower temperatures, χ becomes essentially temperature independent, until about 20 K, where a rise with further cooling is often dominated by impurities. Unlike Ni, which is just above Pd in the Periodic Table, Pd does not become magnetic because 4d-4d wave function overlap prevents the satisfaction of the Stoner criterion for band magnetism, $S = \infty$.

$$S = 1/[1 - N(E_F) \bar{I}] = T_o/T_{sf}; T_{sf} \sim -\Theta_{CW} \quad (1)$$

where S , is the exchange enhancement, $N(E_F)$ the density of electron states at the Fermi level, $\bar{I}$ the interaction parameter and T_{sf} the spin fluctuation parameter (which is about 260 K for Pd). It had been known for some time that high pressures cause a drop in χ for Pd [5]. Since $S = \chi/\chi_o$, where χ_o is the band susceptibility (and $\Delta S \approx \Delta\chi/\chi_o$), it follows that the exchange enhancement also drops at high pressures, if $\bar{I}$ remains constant. This is readily understood from band calculations which show that $N(E_F)$ drops as a_o decreases and rises as a_o increase [6].

In the present work, Pd was grown epitaxially on Au(100) or Ag(100) as A-Pd-A, where both Au and Ag have a_o 's 4.7% larger than that of Pd. At each A-Pd interface there is a 2.4% stretching of the Pd lattice, which decreases to zero towards the center of the Pd film. Generally, sample thicknesses of around A(100)-B(1.5)-A(100), all in nm, were used.

In the case of A-Cr-A, Thomas and Haas [7] have found in a LEED and work function study that Cr grows as the fcc structure on Au(111). Our transmission electron microscope, TEM, studies [8], support the occurrence of fcc Cr

on Au(100), also. since the known antiferromagnetism of Cr is a consequence of its particular Fermi surface in the bcc structure, it is to be expected that its magnetic behavior is also affected by the structural change.

2. RESULTS

Fig. 1 shows the plot of $1/\chi$ vs T for four samples of Au-Pd-Au at low temperatures (see Table I for a summary of samples and results). The data have been fitted to a Curie-Weiss law, which seems reasonable from the figure. The range of θ_{CW} values, $-(0.1$ to 7.5 K), yields T_{sf} values of 0.1 to 7.5 K, which means that the samples are nearly magnetic. This is seen also from the magnitude of the χ values which range from 28-514 times the value for bulk Pd. In addition to the results shown in fig. 1, several other samples also showed large increases in their χ values, but temperature dependences could not be ascertained (see Table I). It should be noted that the extremely small sample size, ~ 10 - 100 μg , caused great scatter in the data. The inset of fig. 1 shows that sample IV is probably still paramagnetic even at 2.6 K, although the positive intercept for $H = 0$, could be indicative of an induced or remanent magnetic moment.

Susceptibility data were obtained, also, for one Ag-Pd-Ag sample which yielded χ/χ_{bulk} of 100, but no temperature dependence was discernible. Thus, this system may give rise to a uniform enhancement of the paramagnons, rather than a strengthening of the local moments. Furthermore, measurements of the electrical resistivity, ρ , vs T , show minima in ρ at 11 K, as is shown in fig. 2. This is similar to results found for Ag-Pd alloys having 45-75% Pd [9]. The ρ -minima are due to a strong local exchange enhancement at the Pd site as a consequence of d-band narrowing in Ag-Pd.

χ -T data for Au-Cr EMFS samples are similar to those of Au-Pd, in that Curie-Weiss plots can be used for the highly enhanced susceptibilities ($\chi/\chi_{\text{bulk}} \approx 200$) and $\Theta_{\text{CW}} \approx -1.5$ K. These results, coupled with drops in the ρ -T curves at 2.4 K for other samples were originally attributed to a lowered antiferromagnetic T_N [1]. However, further analysis [2,3] showed that the ρ -drop was due to superconductivity. Fig. 3 shows the ρ -T curves for one sample, XXIIIA, of Au-Cr-Au as a function of applied magnetic field. These data, taken with the field, H , perpendicular to the film are indicative of superconductivity rather than antiferromagnetism, i.e., relatively low H 's shift the transition to substantially lower temperatures and a strong anisotropy is observed in the critical field with $H_{c\parallel}/H_{c\perp} = 4.9$. These results for $H_{\parallel}$ and $H_{\perp}$ are plotted in fig. 4 as H_c vs T . Four out of eight Au-Cr-Au samples showed the superconductivity and their properties are summarized in Table II. T_c 's as high as 3.00 K were observed and these were found to decrease with time at room temperature. No Ag-Cr-Ag samples have been found to be superconducting. All Au-Cr-Au which do not superconduct and all Ag-Cr-Ag samples have ρ -T minima.

Quite surprisingly one sample of Ag-Pd-Ag, XVIIIA1, showed ρ -T behavior quite similar to that of the superconducting Au-Cr-Au. The results for $H_{c\perp}$ are shown in fig. 5. Again, there is a strong anisotropy with $H_{c\parallel}/H_{c\perp} = 8.0$. Table II lists properties of this superconducting Ag-Pd-Ag sample, also. The initial T_c of 2.15 K had dropped to 0.976 K when the data were taken for fig. 5.

3. DISCUSSION

This section will discuss several of the phenomena described above, viz., very large enhancements of χ for Pd; local moment and/or superconducting ρ -T

curves for Cr and Pd; and observations of property modifications in EMFS by other authors.

As indicated in the Introduction, large increases in χ due to lattice stretching in Au-Pd-Au follow simply from the Stoner model and an increased $N(E_F)$. The calculated increase in $N(E_F)$ of $\approx 8.4\%$ for $\Delta a/a_0$ of 2.3% yields $\chi/\chi_0 = 40$ for $\bar{I}N(E_F) = 0.9$ ($S=10$) and no change in $\bar{I}$. Substantially higher χ/χ_0 values are achieved very quickly as $\Delta N(E_F)$ is increased above 8.4%, reaching 100 at 10% and 1000 at 11%. In addition to a simple lattice expansion, the consequences of non-cubic symmetry at the Au-Pd interface must be considered. This can be seen from the calculations of Jarlborg and Freeman [10], who obtain $\chi/\chi_0 = 400$ for tetragonally distorted Pd, and predict metamagnetism. An analysis of recent high pressure data by Gerhardt, et al. [11] led to the conclusion that the drop in $N(E_F)$ is essentially offset by a rise in $\bar{I}$ leading to a very small drop in S with increasing pressure. These results were taken to negate the explanation of a large rise in χ in Au-Pd-Au as being due to a "negative pressure" effect. However, calculations of $\Delta S/S$ or $\Delta\chi/\chi_0$ via the Stoner model (eq. 1) are not symmetric in pressure/volume. Whereas a 10% increase in $N(E_F)$ (for constant $\bar{I}$) causes $S = \chi/\chi_c$ to rise to 100 (or ten-fold), a 10% decrease in $N(E_F)$ only yields a drop in S from 10 to 5. Newer results of Jarlborg and Freeman [12] indicate that $\bar{I}$ is maintained essentially constant as the Pd lattice is distorted. However, their earlier calculations [10] show that the distortion must be considered along with the lattice expansion.

A very sensitive check of the interrelationship between the exchange enhanced χ , $\Delta S = \Delta\chi/\chi_0$, and the Θ_{CW} values is possible. From eq. 1, $\Theta_{CW} = -T_{sf} = T_0/S$. Thus, the values of S may be calculated from two separate aspects of the data ($\Delta\chi$ and Θ_{CW}), and these have been found to be in

reasonable agreement [1]. Furthermore, in a strong spin-fluctuation system, χ is expected to vary as T^2 [13]. That dependence is shown to be followed in fig. 6, within the scatter of the data for sample IV. This yields $T_{sf} = 11$ K, in good agreement with $T_{sf} = 7.6$ K from Θ_{CW} . Interestingly, the ratio of these T_{sf} values (1.4) is the same as that found for the well documented spin fluctuation solid, UAl_2 , using T_{sf} from the specific heat data and χ [14].

The occurrence of minima in the ρ - T curves of Au-Cr-Au (as well as in Ag-Cr-Ag) is easily understood in terms of intermixing during sample preparation leading to Au-Cr alloys which carry local moments down to their Kondo temperature of ≈ 0.01 K [15]. With the LEED and TEM evidence for fcc Cr [7,8], the lack of antiferromagnetic ordering is not surprising. The observation of superconducting transitions in fcc Cr must then be related to the high $N(E_F)$ expected for this structure from an extrapolation of data for fcc Co or Ti [16]. More importantly, a band calculation for fcc Cr with a_0 from the LEED data, or 0.37 nm, yields the Fermi energy at a peak in $N(E_F)$ and $N(E_F) = 2.15$ states/(eV-atom) [17]. It is impossible to calculate T_c without any information about the phonon spectrum for fcc Cr. However, using Θ_D for fcc Ni, or 450 K, a $T_c = 2.6$ K is calculated [17]. This value is clearly too low compared to the present results when the normal-state proximity effect is considered (see Table II). Brodsky and Hamaker [3] have shown that for the film thicknesses of sample XXIIIA $T_c > 10$ K for bulk fcc Cr is necessary to fit the initial experimental value of 2.11 K. Recent work with Au-V-Au and Ag-V-Ag EMFS [3,8] indicate that fcc V may be present on Au, also, with a T_c below that of bcc V.

The discussion of the Au-Cr-Au and Ag-Pd-Ag data in terms of a superconducting transition is further supported by the $H_{c2} - T_c$ dependences (since the sample thicknesses are all less than the coherence lengths [2,3], the system

is in the mixed state (even for $H = 0$). Following Fischer [18], the orbital contribution to H_{c2} , $dH_{c2||}^*/dT|_{T=T_c} = dH_{c2||}/dT|_{T=T_c}$. Values of 42 kOe/K for XXIIIA and 71 kOe/K for XVIIIA1 were observed with T_c 's near 1 K (see also Table II). Using derived ρ 's and estimated $N(E_F)$'s, calculated values of 32 kOe/K for XXIIIA and 10 kOe/K for Ag-Pd-Ag sample XVIIIA1 are obtained [2,3]. The agreement is good for the Au-Cr-Au sample and the disagreement for the Ag-Pd-Ag sample is due to the sample not being in the dirty limit. The results for XVIIIA1 lead to a calculated mean-free-path of 32 nm, vs a coherence length of $\lambda_c \approx 6$ nm.

It is worth remembering that all Au-Cr-Au, Ag-Cr-Ag and Ag-Pd-Ag samples that were not superconducting, had minima in their ρ -T curves. Since this occurrence seems to be indicative of local-moment or very strong spin-fluctuation behavior, the proximity effect plus local-moment occurrences should diminish T_c , strongly. The explanation of this effect as being due to interdiffusion is supported by the behavior of the ρ -T curves of superconducting Au-Cr-Au (XXIIIA) and Ag-Pd-Ag (XVIIIA1) samples when stored at room temperature for long periods of time. For example, sample XXIIIA showed a somewhat linear drop in T_c with time of ≈ 1 K/250 days [3]. Furthermore, a minimum became apparent in the ρ -T curve after T_c dropped below 1.8 K, or after 64 days at room temperature. Similar behavior was seen for sample XVIIIA1, Ag-Pd-Ag.

Whereas the superconductivity for fcc Cr follows directly from its high $N(E_F)$ and the apparently greater ability to prepare samples without alloying, the situation for Ag-Pd-Ag is less clear. Superconductivity has been found in Pd which was irradiation damaged, where presumably the effect of the spin fluctuations was eliminated [19]. Disordered bcc Cr also has been found to be a superconductor [20]. The occurrence of superconductivity in the highly

exchange enhanced Ag-Pd-Ag EMFS is not likely due to p-wave pairing [21]. The layer-dependent a_0 causes a great deal of electron scattering, even though the sample is not fully in the dirty limit, which is highly detrimental to triplet superconductivity [21]. More likely, there is some intermixing of the Pd and Ag at their interfaces, which reduces the spin fluctuations and allows superconductivity while $N(E_F)$ is still large [22]. Observation of the enhanced temperature-independent χ in the one sample measured is indicative of a high $N(E_F)$ without the concurrent formation of local moments. Note, however, that superconductivity has not been found down to 0.1 mK in Ag-Pd alloys [23].

Although the present work has emphasized EMFS where the "magnetic" component, Pd or Cr, is covered by an outer layer of the epitaxial metal (i.e., A-B-A), there are also interesting results for sandwiches of the type A-B. Gradmann and Isbert [24] have related the magnetic moment of fcc γ -Fe on (111) surfaces of Au-Cu alloys to the a_0 of the alloy. Thus for $a_0 > 0.365$ nm, Fe films two atom layers thick had strong ferromagnetism, i.e., magnetic moments of $2.6 \mu_B/\text{Fe}$. Conversely, for $a_0 < 0.365$ nm, the Fe moment was a function of a_0 , dropping to $0.6 \mu_B/\text{Fe}$ at pure Cu. In a different type of experiment, Bergmann [25] found that a monolayer of Ni on Pb-Bi alloys carried no magnetic moment, whereas monolayers of Co and Fe are magnetic on Pb-Bi. These films are deposited at low temperatures and not epitaxial, but are probably relevant to the properties considered here. Bergmann has also found similar results for Ni monolayers on Mg, Al and Sn substrates (no moment), but does see magnetic moments for monolayers of Ni on Cu, Ag and Au [26]. The latter result is consistent with the limiting case of a Ni monolayer on Ni. For Ni(110) Celotta et al. [27] have found a finite magnetic moment for the outer layer of Ni atoms via polarized LEED studies in agreement with calculations [28]. Mössbauer studies of Fe(110) EMFS on Ag(111) show an enhanced magnetic moment

in the first three monolayers of Fe [29]. These studies clearly show that for Fe or Ni on a transition metal substrate there are no magnetically "dead" surface layers. A different type of metal film sandwich involves compositionally modulated films, eg.g., Cu-Ni [30]. These may be structurally coherent, also. Thus far these materials yield reduced Ni moments and effects strongly dependent on interface phenomena rather than the modulation.

4. CONCLUSIONS

Epitaxial thin films of magnetic or nearly magnetic metals can be prepared with modified lattice parameters or structures of the metals. In some cases these can lead to a strong modification of the magnetic properties of the metal in question (e.g., Au-Pd-Au), and even create dramatically different properties such as superconductivity rather than magnetism (Ag-Pd-Ag and Au-Cr-Au). Since this area of research is fairly new, it is too soon to know if practical problems of reproducibility or stability can be overcome for these techniques to provide new materials of commercial interest. However, it seems fairly certain that scientific interest will remain exciting for a number of years.

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References

- [1] M. B. Brodsky and A. J. Freeman, Phys. Rev. Lett. 45 (1980) 133; M. B. Brodsky, J. Appl. Phys. 52 (1981) 1665.
- [2] M. B. Brodsky, Phys. Rev. B25 (1982) 6060; M. B. Brodsky, P. Marikar, R. J. Friddle, L. Singer and C. H. Sowers, Solid State Commun. 42 (1982) 675.
- [3] M. B. Brodsky and H. C. Hamaker in Superconductivity in d- and f-Band metals, ed., W. Weber, to be published (1982).
- [4] E. P. Wohlfarth and P. F. de Chatel, Comments Solid State Phys. 5 (1973) 133, and references therein.
- [5] I. A. Svechkarev and A. S. Panfilov, Phys. Stat. Sol. b63 (1974) 11.
- [6] S. G. Das, D. D. Koelling and F. M. Mueller, Solid State Commun. 12 (1973) 89.
- [7] R. E. Thomas and G. A. Haas, J. Appl. Phys. 43 (1972) 4900.
- [8] H. C. Hamaker, P. Marikar and M. B. Brodsky, to be published (1982).
- [9] L. R. Edwards, C. W. Chen and S. Legvold, Solid State Commun. 8 (1970) 1403; A. Murani, Phys. Rev. Lett. 33 (1974) 91.
- [10] T. Jarlborg and A. J. Freeman, Physica 107 B + C (1981) 69.
- [11] W. Gerhardt, F. Razavi, J. S. Schilling, D. Hüser and J. A. Mydosh, Phys. Rev. B24 (1981) 6744.
- [12] T. Jarlborg and A. J. Freeman, to be published (1982).
- [13] M. T. Beal-Monod, S. K. Ma and D. R. Fredkin, Phys. Rev. Lett. 20 (1968) 929.
- [14] R. J. Trainor, M. B. Brodsky and H. V. Culbert, Phys. Rev. Lett. 34 (1975) 1019.
- [15] I. R. Williams, I. A. Campbell, C. J. Sanctuary and G. V. H. Wilson, Solid State Commun. 8 (1970) 125; C. H. Buchal, R. M. Mueller, F.

- Pobell, M. Kubota and H. R. Folle, *Solid State Commun.* 42 (1982) 43.
- [16] V. L. Moruzzi, J. F. Janak and A. R. Williams, *Calculated Electronic Properties of Metals* (Pergamon, New York, 1978) pp. 68-9, 88-9.
- [17] J.-H. Xu, A. J. Freeman, T. Jarlborg and M. B. Brodsky, to be published (1982).
- [18] Ø. Fischer, *Appl. Phys.* 16 (1978) 1.
- [19] B. Stritzker, *Phys. Rev. Lett.* 42 (1979) 1769.
- [20] P. H. Schmidt, R. N. Castellano, H. Barz, B. T. Matthias, J. G. Huber and W. A. Fertig, *Phys. Lett.* 41A (1972) 367.
- [21] D. Fay and J. Appel, *Phys. Rev. B* 16 (1977) 2325; K. Levin and O. T. Valls, *Phys. Rev. B* 17 (1978) 191; M. T. Beal-Monod, *Solid State Commun.* 32 (1979) 357.
- [22] B. L. Gyorffy, A. Pindor and W. M. Temmerman, *Phys. Rev. Lett.* 43 (1979) 1343.
- [23] C. H. Buchal, B. Stritzker, M. Kubota, R. M. Mueller and F. Pobell, *Solid State Commun.* 39 (1981) 771; I. K. Schuller, D. Hinks and R. J. Soulen, Jr., to be published (1982).
- [24] U. Gradmann and H. O. Isbert, *J. Magn. Magn. Matl.* 15-18 (1980) 1109.
- [25] G. Bergmann, *Phys. Rev. Lett.* 41 (1978) 264.
- [26] G. Bergmann, to be published (1982).
- [27] R. J. Celotta, D. T. Pierce, G.-C. Wang, S. D. Bader and G. P. Felcher, *Phys. Rev. Lett.* 43 (1979) 728.
- [28] C. S. Wang and A. J. Freeman, *J. Appl. Phys.* 50 (1979) 1940, and references therein.
- [29] J. Tyson, A. H. Owens, J. C. Walker and G. Bayreuther, *J. Appl. Phys.* 52 (1981) 2487.

- [30] E. M. Gyorgy, J. F. Dillon, Jr., D. B. McWhan, L. W. Rupp, Jr., L. R. Testardi and P. J. Flanders, *Phys. Rev. Lett.* 45 (1980) 57; T. Jarlborg and A. J. Freeman, *Phys. Rev. Lett.* 45 (1980) 653; J. Q. Zheng, C. M. Falco, J. B. Ketterson and I. K. Schuller, *Appl. Phys. Lett.* 38 (1981) 424; W. S. Zhou, W. K. Wong, J. R. Owers-Bradley and W. P. Halperin, *Physica* 108 B (1981) 953.

TABLE I. Properties of Au-Pd-Au films.

Sample	No. of Pd layers ^a	Largest χ [emu/(g-atom)]	Θ_{CW}^b (°K)
II-1	5	0.029	b
II-2	5	0.10	-3.4
III	5	0.020	-4.6
IV ^c	1	0.36	-7.6
V	12	0.006	b
VIII	1	0.07	b
XIII ^c	1	0.20	-0.1
VI	5	0	---
VII	1	0	---
IX-Al-Al ^d	0	0	---
X-Pt-Pd-Pt	1	0	---
XIV-Au-Au ^{c,d}	0	0	---

^aEach layer contains 1.0 nm of, except for IV and V, which are 1.5 nm thick.

^bTemperature dependence not obtainable.

^cInitial Au layer grown at 300 C.

^dContains no Pd.

TABLE II. Properties of Superconducting Cr and Pd EMFS.

Sample No. ^a	T_c, K^b	$(dH_{c2}/dT)_{T_c}$ kOe/K ^c	Sample Thickness, nm
XXIIIA	2.11	42(1.015 K) 52(0.965 K)	Au(73), Cr(1.1)
XXXIVA2	2.40	---	Au(3.9), Cr(1.9) ^d
XXXIVA3	1.50	---	Au(3.9), Cr(1.9) ^d
XXXIVB	3.00	16(2.19 K)	Au(5.0), Cr(1.9) ^d
<hr/>			
XVIIA1	2.15	71(0.976 K) 60(0.909 K) 48(0.892 K)	Ag(170), Pd(2.0)

^aFor identification only.^bGiven here as the temperature at which the ρ -drop began, when first measured.^cThe corresponding T_c at $H=0$ is given in parentheses.^dPrepared as ten sets of layers.

Figures

- fig. 1. χ^{-1} vs T for Au-Pd-Au samples II-2 (diamonds, $\chi^{-1} \times 2$), III (closed circles), IV (squares, $\chi^{-1} \times 10$) and XIII (open circles). Inset shows the magnetization vs H for sample IV at 2.60 K.
- fig. 2. Typical ρ -T curve for Ag-Pd-Ag.
- fig. 3. ρ -T curves for Au-Cr-Au sample XXIIIA as a function of field applied perpendicular to the film. The respective fields, in kOe, are indicated, and $T_c = 1.015$ K at $H=0$.
- fig. 4. Critical field vs critical temperature for Au-Cr-Au sample XXIIIA after 168 days at room temperature ($T_c = 1.015$ K); (a) $H_{\perp}$, (b) $H_{\parallel}$.
- fig. 5. ρ -T curves for Ag-Pd-Ag sample XVIIIA with the magnetic field perpendicular to the film; $T_c = 0.976$ K at $H=0$.
- fig. 6. Susceptibility of Au-Pd-Au sample IV vs T^2 .

SUSCEPTIBILITY (emu/g-atom)