Reply to Vitta's comment on `The effects of overlayer thicknesses on the electrical resistivity of polycrystalline Cu/Cr double-layered thin films'

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REPLY TO COMMENT

Reply to Vitta's comment on 'The effects of overlayer thicknesses on the electrical resistivity of polycrystalline Cu/Cr double-layered thin films'

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Abstract. The oscillatory behaviour of the resistivity of Cu/Cr-II double-layered films, with the Cr overlayers having thicknesses of 8.5–10.0 nm is attributed to the incommensurate–commensurate (I–C) phase transition of SDW. It is shown that the temperature-dependent resistivity of Cr/Cu multilayers described by Vitta exhibits many resistivity anomalies which might be associated with the magnetic transition of Cr.

Vitta has reported that the oscillatory behaviour of our Cu/Cr-II double layers is not due to an I–C transition of the SDW, and the temperature-dependent resistivities of the Cr/Cu multilayers in Vitta's own study are reported as not showing any resistivity anomaly over the temperature range 30–300 K. However, it is clearly seen from figures 1 (a) and (b) that Vitta's temperature-dependent resistivity has many resistivity bumps (or resistivity anomalies) in the temperature ranges 200–300 K and 155–300 K for periodic and quasiperiodic Cr/Cu multilayers, respectively. Before discussing these specific points, we will consider and clarify Vitta's other points.

(1) It can be seen from our electron diffraction patterns in figure 1(a) of [1] that the bcc rings from the 2.0 nm thick Cr overlayer are superposed on the fcc rings from the 17.6 nm thick base Cu layer, whereas in figure 1(b) the bcc rings from the 9.5 nm thick Cr overlayer are very weak despite being thicker than the 2.0 nm thick Cr overlayer. *This discrepancy could be attributed to the fact that the stresses developed in the Cu/Cr film with a Cr overlayer 9.5 nm thick are different in both magnitude and character from that of the Cu/Cr film with a Cr overlayer 2.0 nm thick, because of the known thickness dependence of the stress.* A similar discrepancy has been observed by Hara and Sakata [2] for Cr films deposited at 20 °C and 250 °C, with grains of 5.0 nm and 20.0–40.0 nm diameter, respectively.

(2) In our study [1] we found that the best-fitting values of surface and interface roughness parameters of the Cu/Cr-I double layers, for the grain boundary reflection parameter $R = 0.38$, are $r_1 = 0.102$–0.129 and $r_2 = 0.000$ respectively. Since interface scattering is believed to be strongly influenced by the surface roughness of the base layer, as mentioned by Vitta (p 1, third paragraph, lines 6–8), the derived values of interface roughness parameters can be regarded as the surface roughness parameters of the uncovered base layer. Therefore, the derived values of interface scattering parameters ($r_2 = 0.000$–0.015) seem to be plausible values.

The total resistivity values of our Cu/Cr-I double layers are higher than those of the uncovered base films and bulk sample (see figure 2 and table 1 of [1]). This is an expected behaviour. According to our analysis [1, 3], the increase in resistivity of Cu/Cr-I double layers, with respect to that of the uncovered base films, is caused only by the increased surface scattering, while the increase with respect to that of the bulk sample is caused by both grain boundary and surface scattering. Furthermore, in our study [1] both the bulk copper sample of thickness 301 nm, and the uncovered and covered copper films should contain the same impurities and defects since they have been prepared in the same experimental conditions. *Therefore, we believe that the impurities and defects cannot be responsible for the increase of the resistivity of the uncovered and covered copper films with respect to that of the bulk copper sample.*

(3) de Vries and Broader [4] have also reported that the grain diameter and transport properties of both double layers and multilayers depend strongly on those of the base layer. Vitta has studied the total electrical resistivity of Cr/Cu multilayers, which can be seen in figures (a) and (b) of [5]. *I understand from the terminology of [5] that Vitta's multilayers are such that Cr is a base layer whereas Cr and Cu are alternating layers. However, in our case, Cu is a base layer, whilst Cr is an overlayer. Therefore, we believe, it is impossible to compare our study with Vitta's study.*

Dimmich [6] and de Vries and Broader [4] have shown that in the case of small-grained multilayered films, both grain boundary and interface scattering, which are operative simultaneously with isotropic background scattering, dominate over the excess resistivity, and may reduce the effect of the surface scattering. *From the above considerations, for the Cr/Cu multilayers of Vitta, two dominant sources of scattering should be the interface and grain boundary scattering. Furthermore, the temperature dependence of the total resistivity of the Cr/Cu multilayers should be resulting from both the interface scattering and the temperature-dependent part (the intrinsic resistivity) of the isotropic background resistivity.*

(4) As described extensively in our study [1], bulk Cr has a sinusoidal spin-density wave (ISDW) in AF_1 and AF_2 phases, whose wavelength is incommensurate with the lattice periodicity below the Néel temperature, $T_N = 310$ K. The wavelength of the SDW has been observed to depend strongly on the addition of 3d electrons, stresses, and grain or particle sizes [2, 7–11]. Several authors [2, 8] have reported that on reducing the grain size of a Cr sample, a commensurate SDW structure in the AF_0 phase will be favoured over the AF_1 and AF_2 phase-polarized ISDW structure.

In our study [1], we have observed that the temperature-dependent resistivity of the Cu/Cr-II films with Cr overlayers of 8.5–10.0 nm exhibits an oscillatory behaviour in the temperature interval 100–300 K. *From the above-mentioned studies [2, 8], this behaviour may well indicate that an I–C phase transition of the SDW (or the antiferromagnetic ordering of the commensurate SDW in the AF_0 phase) has occurred in all of the Cu/Cr-II films*, since for the Cr films, with ISDW, a resistivity anomaly occurs only just below T_N [10], but not over such a wide temperature range. Our results are consistent with those of Hara and Sakata [2] for 20 °C Cr films, with commensurate SDW. However, it is impossible to compare our results with those of Bacon and Cowlam [11] on heavily deformed coarse-grained Cr, because their films are highly stressed.

Vitta has studied the total electrical resistivity of the Cr/Cu multilayers in the temperature range 30–300 K. It is clearly seen from Vitta's figures (a) and (b) in [5] that the temperature-dependent resistivity of the periodic and quasiperiodic Cr/Cu multilayers is not linear over the whole temperature range 30–300 K. On the contrary, many resistivity bumps (or resistivity anomalies) can be observed in the temperature ranges of 200–300 K and 155–300 K. These resistivity bumps may represent either the scatter in the data points or resistivity anomalies associated with magnetic transition of Cr.

In figure (a) of [5], a typical resistivity anomaly of 0.12×10^{-8} Ω m at a level of 49.7×10^{-8} Ω m, observed at ∼200–202 K, represents *a factor of only 0.24%*, while an anomaly of 1.87×10^{-8} Ω m at a level of 51.1×10^{-8} Ω m, observed in the range 260–270 K, represents *a factor of only 0.37%*. In figure (b) of [5] a typical resistivity anomaly of 0.14×10^{-8} Ω m at a level of 21.1×10^{-8} Ω m, observed in the range 155–165 K, represents *a factor of only 0.66%*, while an anomaly of 0.14×10^{-8} Ω m at a level of 21.55×10^{-8} Ω m, observed in the range 190–195 K, represents *a factor of only 0.65%*. *Since resistivity measurements accurate to within 0.2% have been reported by Vitta, the data points shown in figures (a) and (b) of [5] represent many resistivity anomalies, but not the scatter in the data points*. However, these resistivity anomalies appear to be considerably different in magnitude and appearance from those observed for our Cu/Cr-II double-layered films.

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