Quenching of the Hopkinson maximum under contamination in the system Gd(0001)/W(110)

Francisco H. Salas*
Departamento de Física, Facultad de Ciencias, Universidad de Oviedo, E-33007 Oviedo, Spain

Manuel Mirabal-García
Centro de Investigación en Ciencias Básicas, Universidad de Colima, 28000 Colima, Colima, Mexico
(Received 23 October 1989)

The anomalous Hopkinson maximum is observed in Gd(0001) thin films at 289±1 K. This value lies about 3 K below the bulk Curie temperature. The incoherent rotations of the magnetization, which may cause the Hopkinson effect, are quenched by the contamination of the samples. The signal attenuation at 289 K after contaminating a film 80 nm thick is found to be $A_V \approx -15.4$ dB. In our observations, the sharpness of the maximum seems to be in itself a good monitor of the cleanliness of the Gd films.

The so-called "Hopkinson maximum," i.e., the local maximum which the initial magnetic susceptibility presents just below the Curie point, may be due to the incoherent rotations of the magnetization during the reversal process in systems with a net magnetic moment which can respond to an applied ac magnetic field.[1,2]

The temperature dependence of the Hopkinson effect[1,3] in some ferromagnets, for example, Co, Fe, Ni,[4-7] and Gd (Refs. 8–10) is very peculiar.

In this Brief Report we present an interesting phenomenon: the sharp Hopkinson maximum, which is observed in an *in situ* ac susceptibility experiment on clean Gd(0001) thin films grown onto "Auger clean W(110) surfaces" in UHV conditions,[10] suffers a clear degradation as a consequence of the contamination of the films. This means that the incoherent spin rotations, e.g., magnetization curling and magnetization buckling,[11] are practically quenched in the system Gd(0001)/W(110) contaminated.

We show in Fig. 1(a) the ac magnetic susceptibility of a clean Gd(0001) sample 80 nm thick (as taken from Ref. 10); T_H and T_C refer to the Hopkinson and Curie temperatures, respectively ($T_C - T_H \approx 3$ K). In this case, the excursion of the maximum below T_C is observed. *De facto,* the Hopkinson maximum of the ac magnetic susceptibility is reminiscent of the satellite summit observed by Weller and Alvarado[12] in the magnetic-exchange scattering asymmetry. In Fig. 1(b) we show an as yet unpublished susceptibility spectrum for the same sample as in Fig. 1(a), but taken at a pressure of 3.2×10^{-8} Torr after contamination of the sample by exposing it to atmospheric conditions during 7 h. Here, the Hopkinson maximum is no longer observed. In order to compare the signal magnitude in both spectra of Fig. 1, we need to normalize them with respect to the frequency,[13,14] with that we obtain the contamination of the 80-nm-thick Gd film produced at the Hopkinson temperature ($T_H = 289\pm1$ K) a signal attenuation of $A_V \approx 20 \log_{10}(0.98/5.8) = -15.4$ dB.

Concerning these results, some aspects may be commented upon. For example, gadolinium, like most rare-earth metals, presents a very high enthalpy of reaction with oxygen, namely, -16.7×10^5 J/mol;[15,16] hence the immense sensitivity of the magnetic properties of the Gd(0001) surface to the details of sample preparation, mainly surface cleanliness. Notice that surface-enhanced magnetic order (SEMO) is only observed on clean Gd

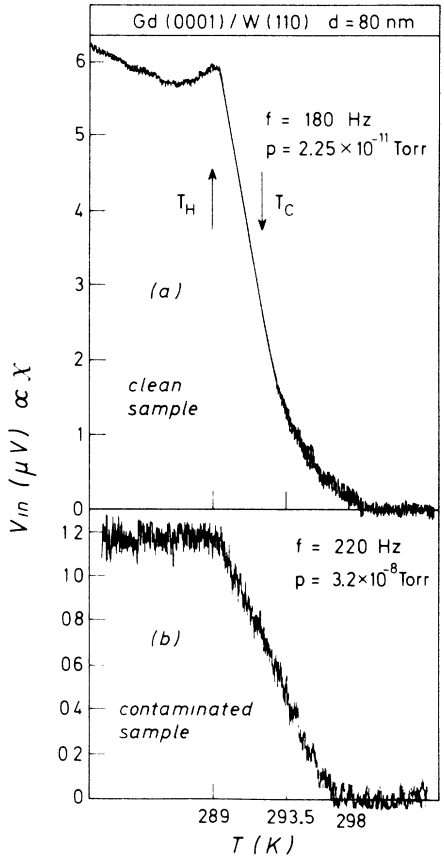

FIG. 1. (a) ac magnetic susceptibility of a clean Gd(0001) film 80 nm thick as a function of temperature (as taken from Ref. 10). T_C and T_H refer to the Curie and Hopkinson temperatures, respectively. (b) ac magnetic susceptibility of the same sample as in (a), after contamination.

samples.[17] Moreover, the contamination of the magnetic Gd(0001) surface by residual gases produces a clear reduction of both magnetic-exchange scattering asymmetry and surface ordering temperature.[12] Likewise, careful spin-polarized photoemission measurements on the surface of polycrystalline Gd have shown[18] a high sensitivity of Gd to hydrogen contamination. Quite recently, LaGraffe *et al.*[19] have investigated the magnetic ordering of thin Gd overlayers by using the method of linearly polarized synchrotron-radiation photoemission. They also observed the high sensitivity of the properties of Gd to contamination. In particular, the energy-distribution curve (EDC) of Gd overlayers (2 ML thick) as taken 3 h after deposition is found to be strongly affected by contamination.

It is important to note that the Hopkinson maximum in Gd is observed in a temperature range where the Gd is magnetically uniaxial, given that the spin reorientation of Gd occurs below 240 K.[20] On the other hand, our butterfly susceptibility measurements[21] have shown that the Gd(0001) samples tend to reach the Stoner-Wohlfarth field threshold at about 165 Oe. This is convincing evidence of the incoherent character of the magnetization processes at low field in the vicinity of the Hopkinson temperature.

It should be pointed out that our measurement method is a bulk-sensitive one which allows us to detect *in situ* 10^{16} atoms/G_{rms}.[10] Additionally, by scanning the film with Auger electron spectroscopy, it was found that the variation on the film thickness was at most $\pm 6\%$. This small inhomogeneity in a thickness of 80 nm is consistent with the coalescence threshold (at thicknesses of 5–10 nm in terms of the Stranski-Krastanow growth mode[22]) reported by other authors.[17]

Regarding the film contamination, Weller and Sarma[23] studied *in extenso* the oxidation mechanisms in the system Gd(0001)/W(110). They found that the oxidation does not proceed beyond the surface atom layer of Gd(0001). In our case, we feel that the effect of film contamination on the magnetic susceptibility is basically a pinning effect on the film surface. We fully agree with Kooi *et al.*,[24] who showed that an oxidized surface layer is effective in pinning the surface spins. In order to explain these results, Wigen *et al.*[25] proposed a simple mechanism. They suggested that the surface layers are still ferromagnetic but have a smaller saturation magnetization than the undisturbed part of the film.

Finally, with respect to the theory on the Hopkinson maximum, to our knowledge, as pointed out by Vonsovskii many years ago,[26] there is no rigorous quantitative explanation for the Hopkinson effect. One of the approaches to this problem is the inclusion theory developed by Kersten,[27] who believes variations in domain-wall energy are brought about by changes of wall area with position due to the presence of nonmagnetic inclusions in the material. In this model, the initial susceptibility is proportional to $M_S/(K)^{1/2}$. Here, M_S is the spontaneous magnetization, and K is the effective anisotropy constant. Kersten encountered an acceptable agreement between theory and experiment for iron, nickel, and cobalt, but only in a limited range of temperatures. As it is stated in Ref. 27, strong deviations from the theoretical prediction are observed where the susceptibility behavior starts to be anomalous. Unfortunately, within the context of this theory, it is not possible to determine the temperature dependence and magnitude of the proportionality factor between susceptibility and $M_S/(K)^{1/2}$.

We call attention to recent work by Popov and Mikhov,[28] which suggests that the thermal activation contribution to the initial thermomagnetic curves with a Hopkinson maximum may be responsible for two important peculiarities: (i) the proximity between the Hopkinson and Curie temperatures, and (ii) the existence of a minimum just below the Hopkinson maximum.

In any case, we hope that our study will stimulate further theoretical and experimental work in this matter. It would be an especially interesting comparison between our results and by theories of others.

We thank Professor K. Baberschke for his support during our research stay at the Institut für Atom- und Festkörperphysik, Freie Universität Berlin (FRG), where these measurements were carried out. We are indebted to M. A. H. Ramírez (Prados de Coyoacán, México, Distrito Federal) for his invaluable support. We would also like to give thanks to Dr. J. Dorantes-Dávila, Dr. J. F. Fuertes, and Dr. A. A. Aligia for fruitful discussions, and Professor J. M. Alameda (Spain), ITESM, Professor E. Olivares Santana (Mexico), and Professor R. Kasza (Austria) for their permanent support. This research was financially supported in part by Consejo Nacional de Ciencia y Tecnología (CONACyT), Mexico, under Grant No. 140101G102-048.

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*On leave of absence from Departamento de Física, Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM), 64849 Monterrey, Nuevo León, Mexico.

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