Magnetic phase transition in two dimensions: An experimental study on a system of amorphous ultrathin-film multilayers

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We report on an accurate experimental determination of the critical exponents of a two-dimensional magnetic phase transition in a system of amorphous ultrathin-film multilayers grown by sputtering from precise magnetization measurements. The critical exponents β, γ, and δ, related to the temperature dependence of the spontaneous magnetization, the initial susceptibility, and the critical magnetic polarization isotherm, respectively, have been obtained using various conventional methods of analysis from the magnetic-polarization data. These critical exponents are found to be in excellent agreement with the two-dimensional Ising model indicating that the morphological defects in the investigated system are not effective in limiting the correlation length. [S0163-1829(98)01605-1]

''Scaling'' and ''universality'' are the concepts developed to understand critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points. Most of the principal ideas in critical phenomena were tested on the Ising model.

It has been of recent interest to develop systems which can show a two-dimensional magnetic phase transition[1] based on the fact that the introduction of anisotropy permits an isotropic two-dimensional Heisenberg system to enter an ordered state at a finite temperature.[2] There have been many reports in the literature presenting the experimental determination of critical exponents corresponding to two-dimensional systems which normally include a single crystallographically ordered monolayer of magnetic atoms atop a nonmagnetic substrate.[3–5] Much of the main work is done on subnanometer thick Fe films on top of a nonmagnetic surface and the critical exponent values are found to be very close to the two-dimensional Ising values. Our interest has been to prepare a system of ultrathin-film multilayers which could show a magnetic phase transition in reduced dimensions.

The samples are $Nb/(Tb_{0.27}Dy_{0.73})_{0.32}Fe_{0.68}$ amorphous ultrathin-film multilayers (the number of layers equals 100) with the Nb layer thickness and the magnetic film thickness approximately equal to 100 and 10 Å, respectively. This ensures an absolute isolation of magnetic layers. A Nb layer of thickness 500 Å is used as a protective layer on top of the sample. The samples are prepared by the rf sputtering technique. Sapphire was used as the substrate material which offered a flat surface for the sample deposition. The samples are characterized by energy dispersive x-ray analysis (EDAX) and the high-resolution transmission electron microscopy (HRTEM) technique which confirmed the composition as well as the amorphous nature of the samples.[6] The diffraction pattern and a Bright field image of HRTEM measurements are shown in Figs. 1(a) and 1(b), respectively. These pictures show not only the amorphous nature of the films but also a very nice growth pattern of the films. It is very well known that the amorphous structure possesses some defects which are inherent and are typically seen in these pictures. These defects could be, mostly, a type of voids. It is also possible that they represent a type of compositional disorder present typically in the amorphous systems. These defects are placed at random in the films. These defects are separated by a distance of about a few nm, as clearly seen in Fig. 1(b). Normally, the presence of defects is expected to alter the universality class, in the sense that they limit the correlation length from diverging. However, we prove in the next part of our paper that this is not the case with the samples studied in the present work. Our earlier attempts with a Cr layer as the interlayer yielded three-dimensional Heisenberg critical exponents because of the magnetic nature of Cr.[6] Magnetization measurements have been performed with a Quantum Design superconducting quantum interference device (SQUID) magnetometer (model MPMS) with the applied field along the plane of the film. Magnetization isotherms at various temperatures in the temperature range embracing the critical region have been recorded at temperature steps of 0.25 K apart with a temperature stability of ± 10 mK. The demagnetization factor is estimated from the low-field magnetization data and the applied field values are corrected for the demagnetization field in order to get the internal field values.

The basic methods that are generally used to analyze the phase transition and get the critical exponents out are (i) by the Kouvel-Fisher method[7] after deducing the spontaneous magnetization and inverse initial susceptibility as functions of temperature by extrapolation of the modified Arrott plot[8] isotherms, (ii) the critical magnetization isotherm, and (iii) the scaling-equation-of state.[9] These methods give the values of the exponents β, γ, and δ which correspond to the spontaneous magnetization, initial susceptibility, and the magnetization isotherm at the Curie point, respectively.

The modified Arrott $[J^{1/\beta}$ vs $(H/J)^{1/\gamma}]$ plot isotherms constructed using our magnetization data are shown in Fig. 2 along with the values of the parameters used to construct these plots. These plots possess the regular features of the modified Arrott plot isotherms. Values of the spontaneous magnetization (J_s) and inverse initial susceptibility (χ_0^{-1} are

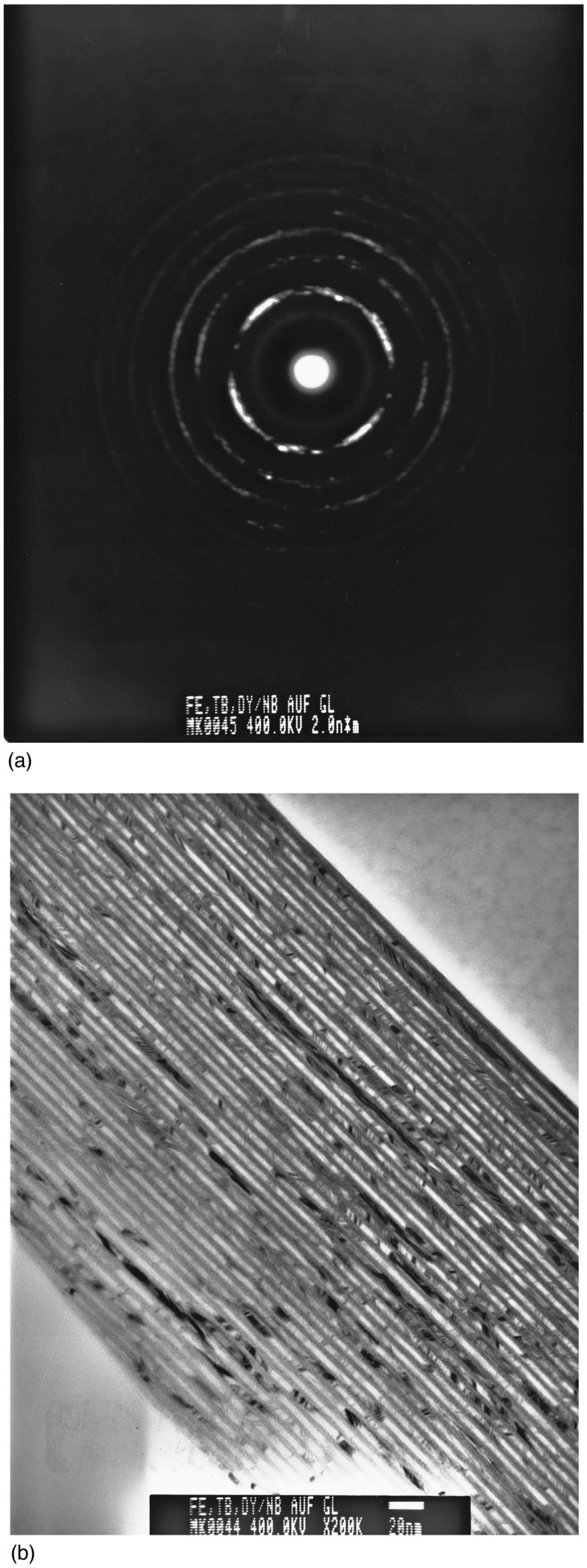

FIG. 1. (a) The diffraction pattern obtained from the sample confirming its amorphous nature. (b) Bright field image of the HRTEM pictures showing a clear layer-by-layer growth of the films.

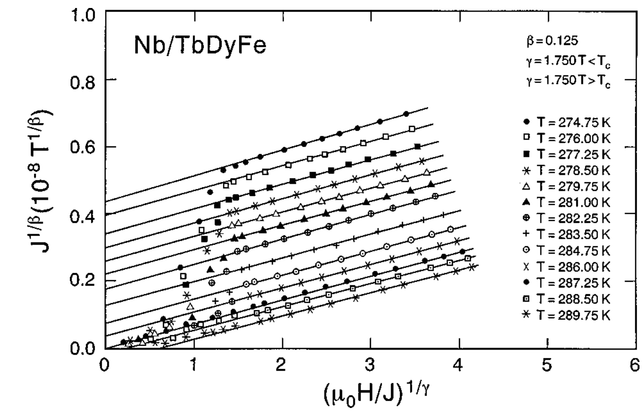

FIG. 2. Modified Arrott plot isotherms constructed from the raw magnetization data. The exponent values used are also shown in the figure.

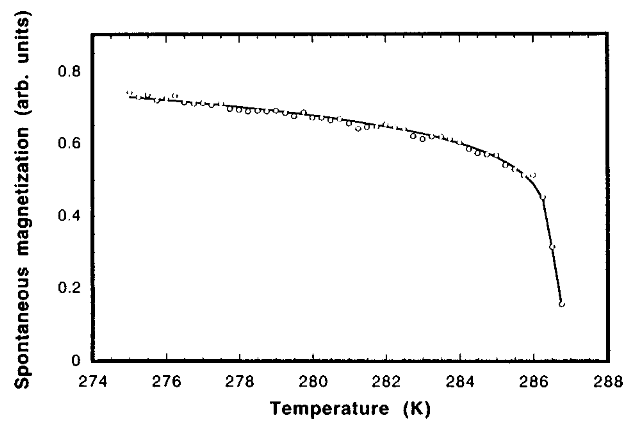

FIG. 3. Spontaneous magnetization plotted as a function of temperature. The continuous line through the data points is the fit to the data based on Eq. (1) of the text.

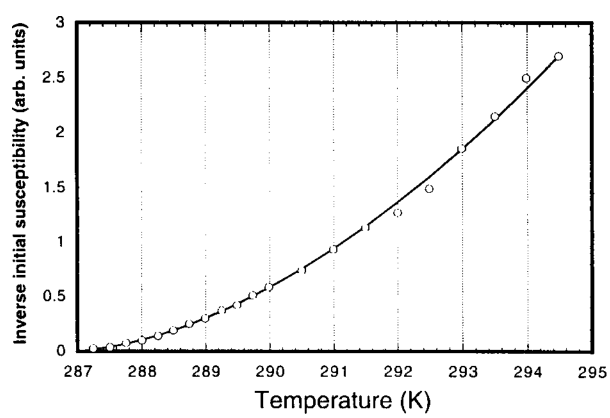

FIG. 4. Inverse initial susceptibility plotted as a function of temperature. The continuous line through the data points is the fit to the data based on Eq. (2).

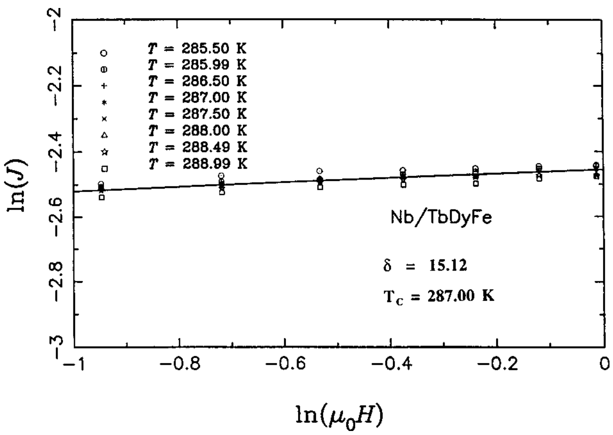

FIG. 5. $\ln J$ vs $\ln \mu_0 H$ isotherms at a few representative temperatures near T_C. The straight line through the data points represents the best least-squares fit to the critical isotherm based on Eq. (3).

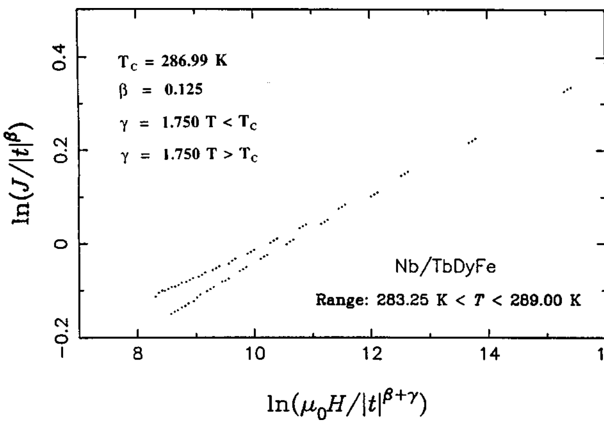

FIG. 6. Scaling plots.

obtained as functions of temperature from the intercepts made by the linear extrapolation of the straight line portions in the modified Arrott plots are shown in Figs. 3 and 4, respectively, wherein the continuous lines through the data points represent the fits to these data made based on the following equations, which include the values of the critical exponent:

$$J_s(T)=j_0(-t)^{\beta}, \quad t<0, \tag{1}$$

$$\chi_0^{-1}(T)=(h_0/j_0)t^{\gamma}, \quad t>0, \tag{2}$$

where j_0 and (h_0/j_0) are the critical amplitudes and $t=(T-T_C)/T_C$. The values of β and γ obtained from the above fits are $\beta=0.126\pm0.020$ and $\gamma=1.75\pm0.03$.

Next, the critical exponent δ is obtained from the magnetization data at T_C using the following expression:

$$J=A_0(\mu_0 H)^{1/\delta}, \quad t=0. \tag{3}$$

The $\ln J$ vs $\ln \mu_0 H$ plots in a narrow temperature range around T_C are shown in Fig. 5 and the exponent δ is obtained from the straight line fit made to the data at T_C.

Now the values of the critical exponents obtained are $\beta=0.126\pm0.020$, $\gamma=1.75\pm0.03$, and $\delta=15.12\pm1.0$. These values are in good agreement with those ($\beta=0.125$, $\gamma=1.75$, and $\delta=15$) theoretically predicted for a two-dimensional Ising spin system.[10] These values of the exponents also satisfy the Widom scaling relation[11] ($\beta+\gamma=\beta\delta$) and hence demand for the validity of the scaling equation of state.

The scaling plots obtained are shown in Fig. 6 wherein it is seen that the data collected at various field values fall on to two different curves, one for temperatures below T_C and the other for temperatures above T_C.This confirms[12] that the values of the exponents and T_C determined by the above methods are reasonably accurate.

It is very interesting to see that these experimentally determined values of critical exponents are identical (within error limits) to those calculated for the two-dimensional Ising model since our system is not a lattice with perfect translational symmetry. The amorphous nature of our samples ensures the absence of perfect translational symmetry. Also in our system. Fe does not have localized spins though rare earths do and this makes some of the spins have more degrees of freedom. Hence, we believe that the very good agreement between the experimental and theoretical values of the critical exponents confirms the universality hypothesis. The values of the critical exponents could be explained by the fact that the numerical values of the critical exponents depend only on (i) the lattice dimensionality of the spin system, (ii) the number of components of the order parameter, (iii) the symmetry of the Hamiltonian, and (iv) the range of the microscopic interactions (mainly exchange) responsible for the phase transition. Although the presence of defects (the presence of defects is ensured by the amorphous nature of the films) is expected to alter the universality class[13] of the phase transition, this is not true with the sample under investigation reflecting the fact that the defects present in the sample are not effective in limiting the correlation length which is much larger compared to the distance between the defects. The observation of such values for the critical exponents means that this phase transition involves spins of individual atoms but not their position and hence the two dimensionality is effectively obtained.

In conclusion, we have studied the magnetic phase transition in $Nb/(Tb_{0.27}Dy_{0.73})_{0.32}Fe_{0.68}$ amorphous ultrathin-film multilayers by deducing the critical exponents β, γ, and δ. These values are found to be in a very close agreement with those predicted, theorectically, for a two-dimensional Ising model.

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