“Size effects in sub-micron exchange bias square elements”

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Abstract:

The behaviour of sub-micron exchange bias square elements has been investigated for systems containing metallic polycrystalline layers. Numerical simulations using a simple theoretical model show that the exchange bias for such elements can increase and/or decrease depending on the microstructure of the antiferromagnetic layer and, in particular, its grain size distribution. The predictions are based on a granular model of exchange bias that accounts for grain cutting at the edges of the nanoelements that takes place during ion milling/etching. This leads to distributions of exchange bias fields that can be quite broad, especially in sub 250nm elements.

Exchange bias refers to the shift of the hysteresis loop along the magnetic field axis of systems consisting of a ferromagnetic (*F*) layer grown in direct contact with an antiferromagnetic (*AF*) layer.[1] From a technological point of view, it has attracted great attention since the introduction in 1991 of a magnetoresistive read head based on anisotropic magnetoresistance (AMR). The implementation of the magnetic tunnel junction (MTJ) sensor in the mid 90s led to the development of magnetic random access memories (MRAM). Although exchange bias has been used in commercial applications for almost two decades, a full understanding of this phenomenon is still missing. The situation becomes more complicated in the nanoscale, where exchange bias in sub-micron elements has been reported to decrease,[2] and/or increase,[3] when compared to the values measured for thin films. For a recent review of exchange bias in nanostructures see Ref. 4.

One of the parameters that limits the development of technologies such as MRAM is the fact that the magnetic elements do not all switch at the same field giving rise to a switching field distribution (SFD).[5] The origin of the SFD lies in the fact that lithographic elements can never be produced to have exactly the same size and shape. This situation is further complicated by microstructural variations such as the grain size and orientation within the elements, the anisotropy of the material and, more pertinently, dipole-dipole interactions between the nanoelements which lead to cross-talk.[6]

In this letter, we present a simple numerical model that can account for the experimental features observed in sub-micron square structures of size L containing metallic polycrystalline *AF* layers. Simulations are performed using typical

parameters for two of the most important *AF* materials from a technological point of view: FeMn and IrMn.

Samples produced by sputtering result in wide distributions of grain sizes and, therefore, wide distributions of energy barriers. Recently,[7] an interpretation of the exchange bias phenomenon based on the thermal fluctuation model of Fulcomer and Charap,[8] has been proposed. The model treats the *AF* as an assembly of randomly oriented, non-interacting grains distributed in size. The distribution of grain sizes D is assumed to be lognormal since that is the case for sputtered thin films. Hence, ln(D) is normally distributed with a mean value μ and a standard deviation σ. Each *AF* grain is assumed to support a single magnetic domain giving an energy barrier of the form,[7]

$$\Delta E = K_{AF} V_{AF} \left[1 - \frac{H^*}{H_K^*} \right]^2 \tag{1}$$

where V_{AF} is the volume of the grain, K_{AF} is the anisotropy of the *AF* grain, H^* is the exchange field from the *F* layer, which lowers the energy barrier to reversal, and H_K^* is a pseudo-anisotropy field similar to the anisotropy field in single domain ferromagnets. Assuming a uniform value for K_{AF} at the temperature of measurement we can write:

$$H_{ex}(T) \propto \int_{V_c(T)}^{V_{set}(T_{set})} f(V) dV \tag{2}$$

where $H_{ex}(T)$ is the magnitude of the loop shift at the temperature of measurement and $f(V)$ represents the distribution of grain volumes in the *AF*. Under ideal conditions there would be an intrinsic value of $H_{ex}(T)$ which is then moderated by the fraction of the bulk of the *AF* that contributes to H_{ex} and also by the strength of the interfacial coupling. The values of H_{ex} reported in this paper correspond to the contribution to

H_{ex} from the bulk of the *AF* given by the evaluation of the integral in Equation 2 and, hence, have no units. Figure 1 shows a schematic diagram of the grain volume distribution within the *AF* where not the whole *AF* is aligned with the *F* layer. Grains with $V>V_{set}$ remain unaligned due to their anisotropy energy being too large. Moreover, grains with $V<V_c$ are thermally unstable at the temperature of measurement. Hence, only the grains in the window delimited by V_c and V_{set} contribute to the loop shift. The two critical volumes are given by:

$$V_C = \frac{\ln(t_{meas} f_0) k_B T_{meas}}{K_{meas}} \tag{3}$$

$$V_{SET} = \frac{\ln(t_{set} f_0) k_B T_{set}}{K_{set}} \tag{4}$$

where t_{meas} is the time of measurement, k_B is Boltzmann's constant, T_{meas} is the temperature of measurement, K_{meas} is the value of the anisotropy at T_{meas}, t_{set} is the setting/annealing time, T_{set} is the setting temperature and K_{set} is the value of the anisotropy at the setting temperature. A temperature dependence of the form $(1-T/T_N)$ is assumed for K_{AF}, where T_N is the Neél temperature of the *AF*.[9]

The *AF* layer is modelled as a granular microstructure following a lognormal distribution with parameters μ and σ. For all the calculations presented in this work $\mu = 2.30$ and $\sigma = 0.27$. The mean grain size in the film is given by $D_m = e^{\mu}$ (~10nm in our simulations). Due to the ion milling/etching process grains at the edges of the nanoelements will be randomly cut leading to an effective grain size distribution which might differ significantly to that for the thin film. Note that for 125nm elements, edge grains can account for up to 25% of the total area assuming $D_m = 10$ nm. This suggests that grains that did not contribute to the loop displacement in the thin film might now contribute to the loop shift and vice versa. The effective grain

size distribution within a given nanoelement is then calculated. The exchange bias for the nanoelements will be given by evaluation of the integral in Equation 2 where *f(V)* has been modified accordingly.

The effect of the element size L, assumed to be square, on the exchange field for FeMn based exchange biased systems is shown in Figures 2 and 3. Figure 2 shows the probability distributions of exchange fields within arrays of nanoelements of different size. For each array the distribution is generated after calculating the value of the exchange field for 10000 nanoelements ensuring good statistics. The parameters used for the simulations are as follows: K_{FeMn}(293K)= 1.80x10^{4}J/m^3,[10] T_{set}= 473K, t_{set} = 5400s, T_{meas} = 293K and t_{meas} = 100s, f_0 = 10^{9}s^{-1}, T_N = 490K, μ = 2.30 (D_m ~10nm) σ = 0.27 and t_{AF} = 10nm. These values are chosen based on standard measurement/setting conditions. H_{ex} increases sharply with increasing element size for L ≤ 500nm. For bigger elements, the exchange bias saturates, equalling the value of H_{ex} for thin films as indicated by the dashed line in Figure 3. On the other hand, the width of the distribution decreases as the element size increases.

The median exchange bias field for each array as a function of element size is shown in Figure 3. The error bars correspond to the standard deviation of the distributions in Figure 2. For element sizes <300nm distributions as broad as 32% are observed. These results are in excellent agreement with the work of Sasaki *et al.*[2]

Similar calculations have been performed assuming parameters typical of IrMn. In this case we have examined the effect of the *AF* layer thickness on the exchange field at constant element size. For the calculations shown in Figures 4 and 5,

K_{IrMn}(293K)= 5.5x10^{5}J/m^3, T_{set} = 550K and T_N = 690K.[11] The thickness of the *AF* layer was varied between 5 and 19 nm while L = 90nm in all cases. These values were chosen so the theoretical predictions could be compared to experimental results available in the literature.[3] The other parameters were kept the same as for the FeMn simulations. Figure 4 shows the probability distributions of exchange bias fields as a function of *AF* thickness. It is clear from this figure that for thick *AF* layers (t_{AF}≥10nm), t_{AF} does not have a significant impact on the width of the distribution. However, for thinner samples, an enhancement in the standard deviation of the distribution is observed.

Figure 5 shows the median exchange bias field and standard deviation as a function of *AF* thickness for the nanoelements (solid symbols) as well as for thin film samples (empty symbols). For samples with t_{AF}>5 nm the exchange bias does not vary significantly as a function of t_{AF} in the patterned samples. Moreover, above t_{AF} ~10nm the exchange bias is higher for the nanoelements. On the other hand, for low *AF* thicknesses, the exchange bias is higher for the thin films. This is due to the fact that for thick *AF* layers, a significant fraction of the grains lie outside the window delimited by V_c and V_{set}. Increasing the thickness of the *AF* layer increases the grain volume, not the grain diameter, resulting in a greater fraction of the *AF* that cannot be set. Upon patterning, some of these grains will be cut resulting in a larger number of grains contributing to the loop shift. These results are in excellent agreement with the work of Baltz et al.[3]

In conclusion, we have shown that features observed in sub-micron metallic polycrystalline exchange bias elements can be explained in terms of a simple granular

model that takes into account grain cutting at the edges of the nanoelements. This leads to a wide distribution of exchange bias fields for elements below 250nm. Control of the *AF* microstructure can lead to better, i.e. narrower, switching properties. The exchange field can both increase and decrease depending on material parameters, specifically the grain size distribution and anisotropy of the *AF* material.

[1] W.H. Meiklejohn, and C.P. Bean, Phys. Rev. **102**, 1413 (1956).

[2] I. Sasaki, R. Nakatani, K. Ishimoto, Y. Endo, Y. Shiratsuchi, Y. Kawamura, M. Yamamoto, J. Magn. Magn. Mat. **310**, 2677 (2007).

[3] V. Baltz, J. Sort, S. Landis, B. Rodmacq, and B. Dieny, Phys. Rev. Lett. **94**, 117201 (2005).

[4] J. Nogues, J. Sort, V. Langlais, V. Skumryev, S. Suriñach, J. S. Muñoz, M. D. Baro, Phys. Rep. 422, 65 (2005).

[5] W.C. Jeong, J.H. Park, G.H. Koh, G.T. Jeong, H.S. Jeong, and K. Kim, J. Appl. Phys., **97** 10C905 (2005).

[6] X. Zhu, P. Grütter, Y. Hao, F. J. Castaño, S. Haratani, and C. A. Ross, J. Appl. Phys. **93**, 1132 (2003).

[7] G. Vallejo-Fernandez, L. E. Fernandez-Outon, and K. O'Grady, J. Phys. D: Appl. Phys. **41**, 112001 (2008).

[8] E. Fulcomer, and S. H. Charap, J. Appl. Phys. **43**, 4190 (1972).

[9] M. D. Stiles and R. D. McMichael, Phys. Rev. B **60**, 12950 (1999).

[10] L. E. Fernandez-Outon, G. Vallejo-Fernandez, S. Manzoor, B. Hillebrands, and K. O'Grady, J. Appl. Phys. **104**, 093907 (2008)

[11] G. Vallejo-Fernandez, L. E. Fernandez-Outon, and K. O'Grady, Appl. Phys. Lett. **91**, 212503 (2007).

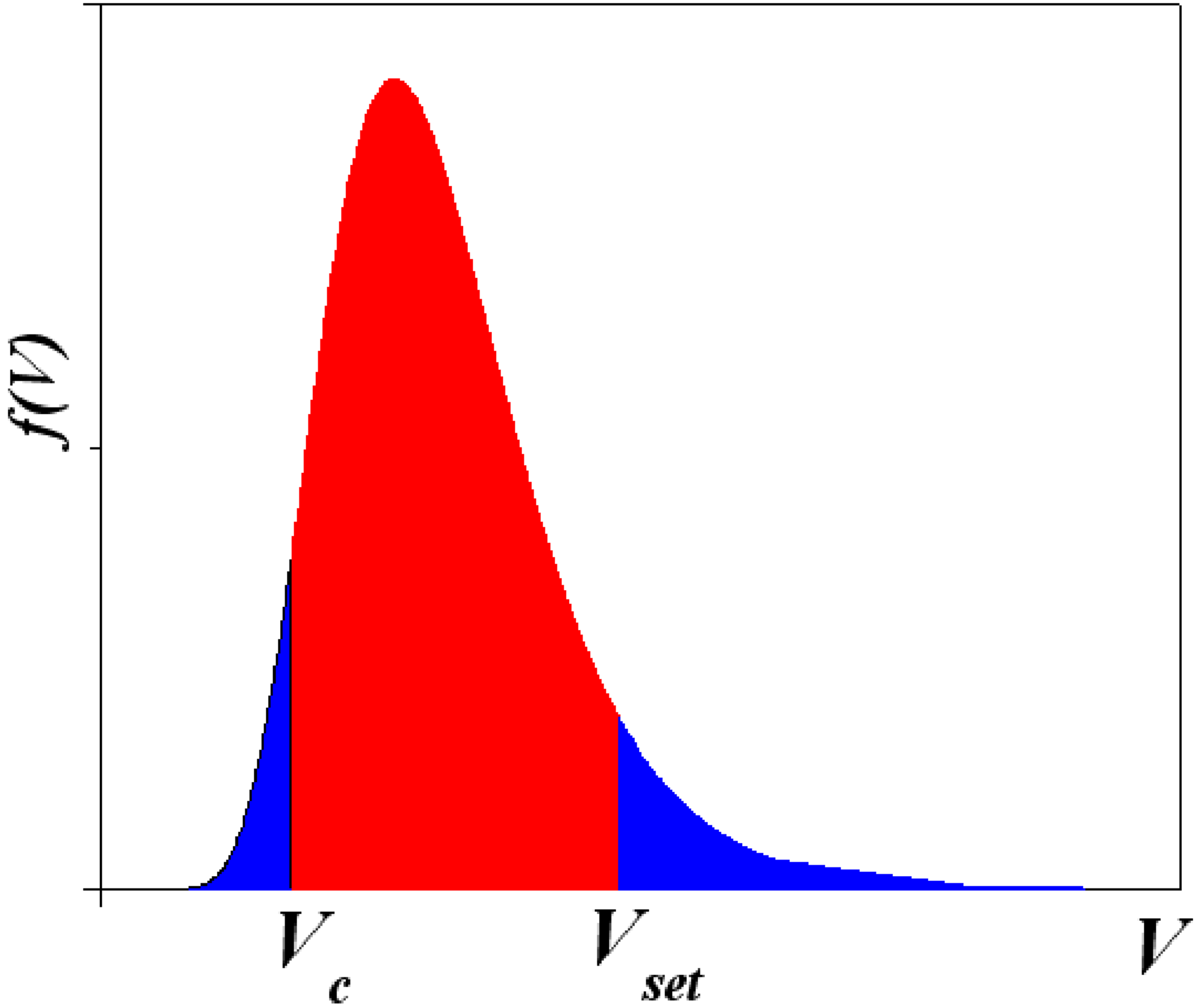
Figure 1. (colour online only) Schematic of the grain volume distribution in the *AF* after setting a fraction of the *AF* and cooling to a temperature where some of the smaller *AF* grains remain thermally unstable.

Figure 2. (colour online only) Distribution of exchange bias fields for systems containing an FeMn AF layer as a function of the element lateral size. The lines are guides to the eye.

Figure 3. (colour online only) Variation of the median exchange bias field with the element size L for FeMn exchange biased systems. The line is a guide to the eye.

Figure 4. (colour online only) Distribution of exchange bias fields for systems containing an IrMn *AF* layer as a function *AF* thickness for constant element size (L = 90nm). The lines are a guide to the eye.

Figure 5. (colour online only) Variation of the exchange bias as a function of the thickness of the *AF* layer for nanoelements (solid symbols) and thin films (open symbols). The lines are a guide to the eye.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V
c
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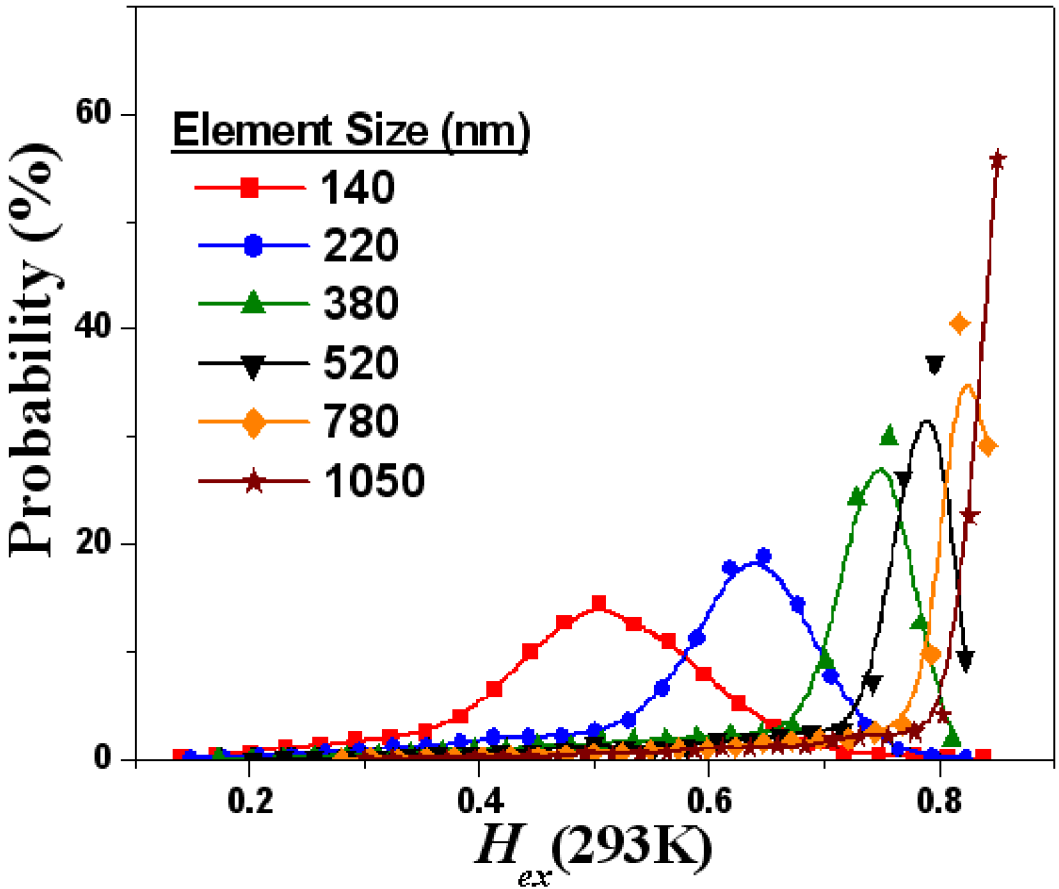
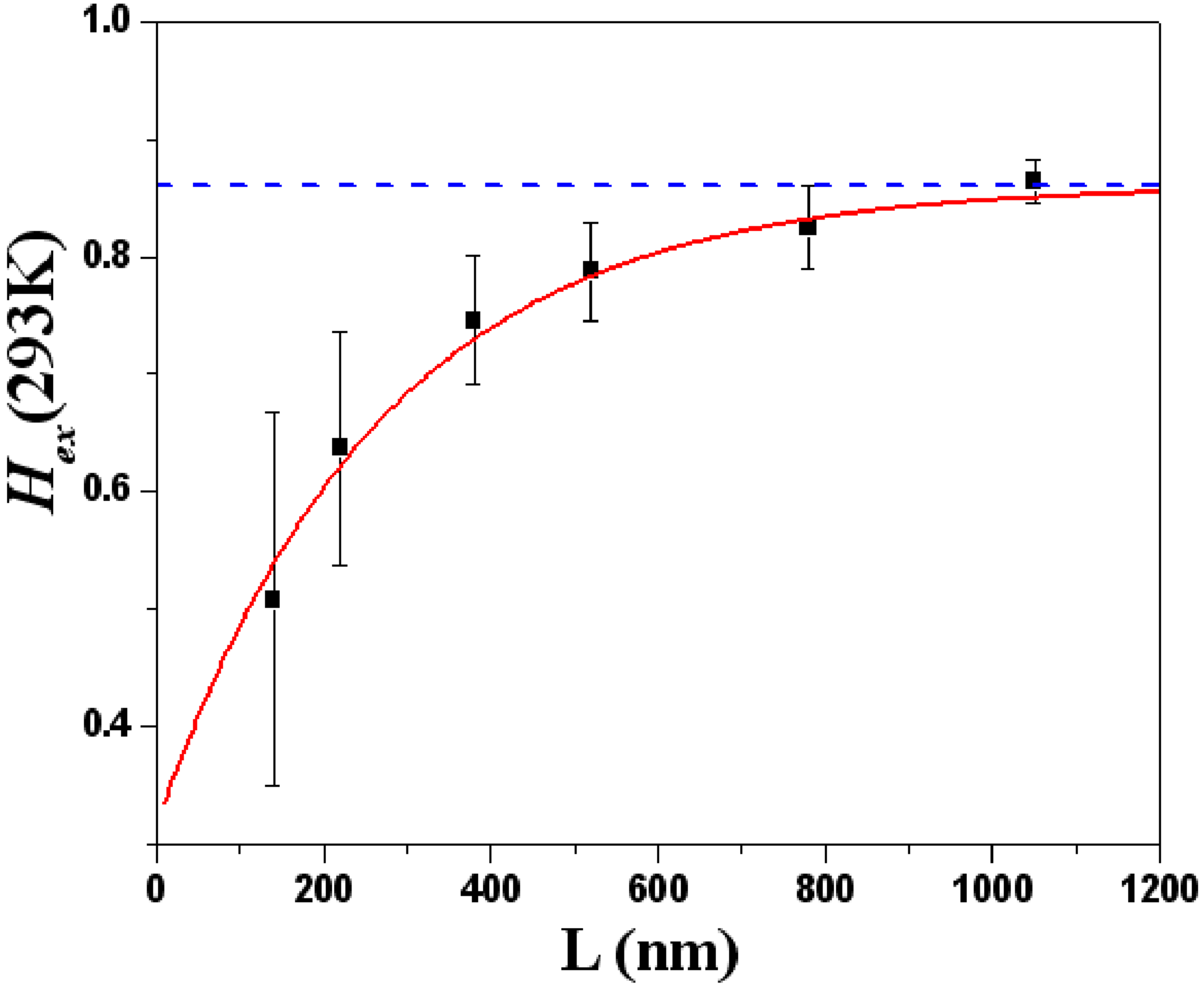
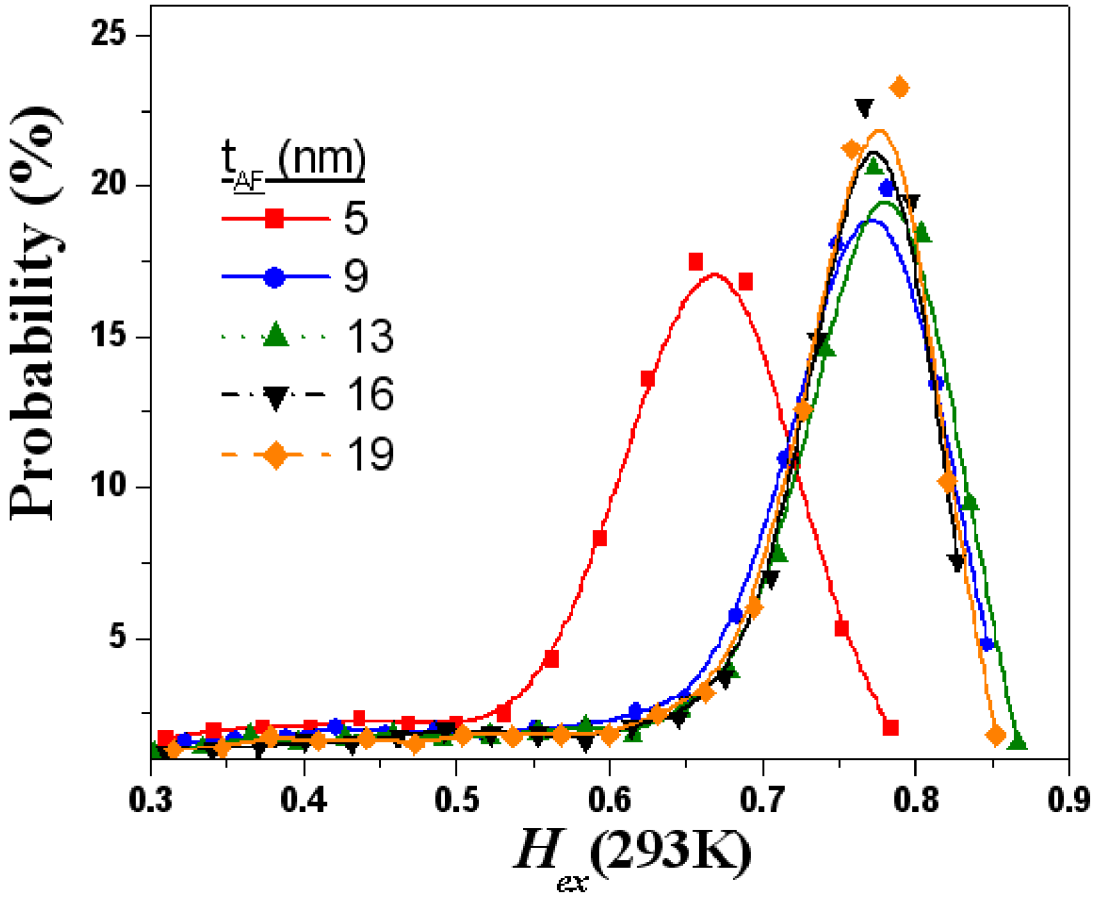
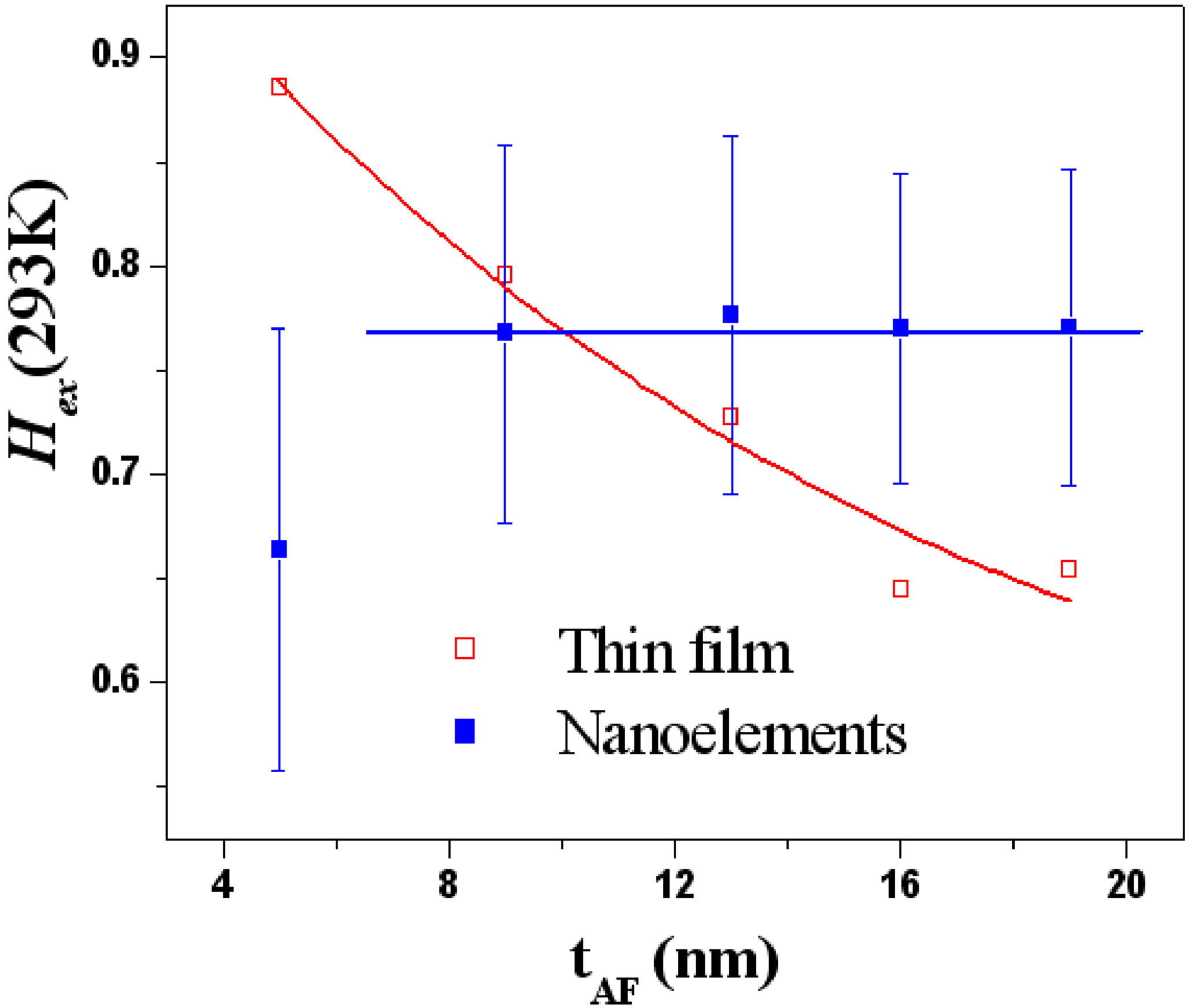
V


Element Size (nm)
140
220
380
520
780
1050
Probability (%)
60
40
20
0
0.2
0.4
0.6
0.8
H_{ex} (293K)


1.0
0.8
0.6
0.4
H_{ex}(293K)
0
200
400
600
800
1000
1200
L (nm)


Probability (%)
25
20
15
10
5
t_{AF} (nm)
5
9
13
16
19
0.3
0.4
0.5
0.6
0.7
0.8
0.9
H_{ex} (293K)


0.9
0.8
0.7
0.6
H_{ex} (293K)
4
8
12
16
20
t_{AF} (nm)
Thin film
Nanoelements