Magnetic order in Graphite: Experimental evidence, intrinsic and extrinsic difficulties

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1. Introduction

The possibility to have magnetic order at room temperature in a system without the usual 3d metallic magnetic elements has attracted the interest of the solid state physics community in recent years. According to recent theoretical studies [1,2,3,4,5] the graphite structure with defects and/or hydrogen appears to be one of the most promising candidates to find this phenomenon. Early reports in the decades of the 80's and 90's indicate the existence of magnetic order in some carbon-based samples (see [6] and Refs. therein). However, difficulties to reproduce those results and the unclear role of impurities casted doubts on its existence. The nowadays technique allows us to measure the amount of magnetic impurities with high enough accuracy especially in carbon-based materials. However, inappropriate sample handling added to the possibility of non-simple phase transformations of magnetic elements after sample preparation (as in the case of magnetic fullerene [7,8]), possible aging effects as well as the rather small magnetic signals of the magnetic carbon samples, make the research in this area of magnetism rather difficult.

A few years ago a first study of proton irradiation effects on the magnetic properties of highly oriented pyrolytic graphite (HOPG) has been reported [9]. After this experimental study theoretical estimates of the magnetic moments at certain lattice defects produced by irradiation followed [10,11]. The introduction of defects in the graphite structure by irradiation should be in principle an ideal method to test any possible magnetic order in carbon since it allows to minimize sample handling and to estimate quantitatively the produced defect density in the structure. The main magnetic effects produced by proton irradiation have been reproduced in further studies [12,13]. X-ray circular magnetic dichroism (XMCD) studies on proton-irradiated spots on carbon films confirmed that the magnetic order is correlated to the π-electrons of carbon only, ruling out the existence of magnetic impurity contributions [14]. Apparently, the reproducibility of the above reported effects by independent groups is not yet satisfactory. Taking this fact into account the aim of this contribution is not only to discuss new evidence that speaks for the existence of metal-free magnetic order in graphite but also on the intrinsic and extrinsic difficulties to trigger and measure its in general small magnetic signals.

2. Impurity measurements, Intrinsic and Extrinsic Difficulties

2.1. Impurities Measurements

Taking into account old [6] as well as recently published results [9,12,13,14,15,16] and the amount of ferromagnetic mass on one may trigger with a single-energy proton beam (see sec. 2.2) we expect ferromagnetic moments at saturation of the order of several tens of μemu for typical sample masses, at best. Therefore, one requires that: (a) the total amount of magnetic impurities in the samples should be low enough to provide a nominal ferromagnetic moment of at most one order of magnitude smaller than the expected ferromagnetic moment at saturation and produced by the irradiation, e.g. ~ 5 μemu. (b) The use of a method to characterize the impurities with low enough detection limit.

For pure Fe one needs a mass m = 23 ng to produce a magnetic moment of ~ 5 μemu. This means a volume of ~ 3 x 10⁻⁹ cm³, i.e. a cube of ~ 14 μm size. Taking into account the typical graphite sample mass used for SQUID measurements, this means to have a relative impurity concentration of ~ 6 μg/g. The characterization method used by us and called Particle Induced X-ray Emission (PIXE) pro-
Fig. 1. (Color online) Iron distribution obtained by PIXE within ~ 30 µm depth of a HOPG sample (0.4° rocking curve width). The Fe distribution is in this case non-homogeneous, even within a Fe spot (right picture). Rutherford backscattering (RBS) data reveals a nearly two-dimensional Fe distribution at the spot. The total Fe concentration in this sample is 0.6 µg/g equivalent to ≲ 0.15 ppm.

provides the needed detection limit (≲ 0.1 µg/g) for all typical magnetic elements embedded in the carbon matrix.

The main magnetic impurity in HOPG samples is Fe. Figure 1 shows the Fe distribution of a typical HOPG sample. The overall Fe content is 0.6 µg/g, i.e. less than 0.15 ppm. This quantity is in general higher than in most of the HOPG samples we have measured from the same company (Advanced Ceramics). To check this number and the overall calibration of our system, the impurities content of another HOPG sample has been measured by Neutron Activation Analysis (18 days activation time with 6 h. measuring time) and by PIXE, both providing the same result of 0.17 ± 0.03 µg/g of Fe. Other magnetic impurities are clearly below this number. This means that the whole amount of Fe, if ferromagnetic, would give a maximum magnetic moment < 0.5 µemu. Clearly, we have to assure that the whole sample handling does not provide additional impurities, see Sec. 2.3.

In a recently published study the magnetic properties of HOPG samples after implantation of Fe have been studied [17]. No particular influence on the ferromagnetic properties of HOPG was observed after up to ~ 4000 µg/g (0.08 at%) Fe-concentration in the implanted region. On the other hand, the implantation produced a clear increase in the paramagnetic contribution, which is caused by the structural disorder created by the ion bombardment. Even a heat treatment of the Fe-implanted HOPG samples, which reduced the paramagnetic contribution, did not produce additional ferromagnetism [17]. The absence of a ferromagnetic contribution after Fe-implantation indicate that iron impurities in carbon not necessarily trigger ferromagnetism. This result also indicates that a highly disordered, nearly amorphous carbon lattice, as it was the case after Fe-implantation, does not show magnetic order.

2.2. Intrinsic Difficulties

(a) In spite of some differences in the models that use limited sample size and different algorithms for the calculations, all recent theoretical results indicate that defects, e.g. vacancies or hydrogen add atoms, in the graphene [1,2,3,4,5,18,19] or graphite lattices [18] are a source of finite magnetic moments and the main ingredient to trigger magnetic order. To this consent we should add also the long-range antiferromagnetic exchange coupling between C-neighbors belonging to the two different sublattices of the graphene or graphite lattice [3,4,5]. An unbalance between the vacancy (or defect) distributions in the two sublattices of graphene results in a ferrimagnetic state with a net magnetic moment \( m \propto (N_A - N_B)/2 \), where \( N_{A,B} \) is the number of vacancies in the A or B sublattices [18,19]. The possible role of hydrogen [1,2] and the influence of the stacking order in the graphite lattice [18] complicate further a realistic estimate of the expected magnetic moment after irradiation.

Nevertheless, one expects a rather narrow window of values for several irradiation parameters, like fluence, energy or ion current, necessary to trigger a measurable magnetic signal. It is clear that the selected ion fluence will play a main role because this is one of the parameters that determines the defect density as a function of the penetration depth. A small enough distance between vacancies would trigger a sufficiently large magnetic moment to be measurable with the SQUID. On the other hand, the condition of preserving the graphite lattice – amorphous carbon is not ferromagnetic but paramagnetic [20] – provides a limit to the maximum allowed fluence. Therefore, one expects that at a given fluence at which, for example, the distance between vacancies is of the order of 1 nm, we will have a maximum in the magnetization of the irradiated graphite sample, as has been observed experimentally [9,15,21].

The defect density depends on the penetration depth of the ions in the sample, see Fig. 2. Because we can expect that the total magnetic moment in a sample will be inversely proportional to, at least, the square power of the distance between vacancies, at a given penetration depth only a rather small amount of ferromagnetic mass with large enough value of magnetization can be produced in a sample using a fixed energy for irradiation. Below a given distance between vacancies the crystalline order and therefore the magnetic order will collapse. As an example how to estimate the necessary fluence range to get the largest magnetic signal, we calculate the mean distance between neighboring vacancies obtained from Monte Carlo simulations of the damage produced by 2.25 MeV protons in graphite using the SRIM program [22].

Figure 2(a) shows the dependence of the mean distance between vacancies with the proton fluence \( \phi \) for a two-dimensional (2D) graphene lattice, i.e. the vacancies of adjacent graphene layers are neglected. The vacancies from adjacent graphene layers are taken into account in the 3D graphite lattice estimate, see Fig. 2(b). These estimates were obtained assuming a vacancy production rate of 0.1 vacancies per micron depth interval expected in the first ~ 10 µm depth from the graphite surface for protons of 2.25 MeV energy. Furthermore, the depth dependency of the vacancy production rate given by the SRIM simulation [22] can be used to calculate the mean distance as a function of depth, see Fig. 2(b). Assuming that the largest signal due to the induced magnetic order is produced at a distance between vacancies of 1.5 ± 0.25 nm in the 2D case, different depth intervals contribute to the magnetic signals at different fluences. The calculations indicate that from the three selected fluences in Fig. 2(b) the largest ferromagnetic signal would be given for \( \phi \gtrsim 10^{18} \) protons per cm² at ~ 30 µm depth. These estimates indicate also that the largest ferromagnetic mass one can produce with a single energy proton beam will be located at the first ~ 10 µm depth where the curve is rather flat.

Results obtained in Ref. [13] indicate that the measured magnetic signal coming from irradiated spots was located in the first micrometers depth in qualitative agreement with the estimates presented here. Following the estimates done in Ref. [5] based on the ferromagnetic contribution of coupled defects from the same sublattice of a
graphene lattice, a mean distance between vacancies of 1.5 nm would give a critical temperature of $\sim 450$ K in good agreement with experimental observations [13,21]. We note that due to the statistical process of vacancy production and the simplicity of the model used for the estimate, an error of at least a factor of two is expected for the calculated damage production rates and the derived mean vacancy distance. Note that in our energy range a lower proton energy will decrease the distance between vacancies at a given depth.

(b) Other intrinsic difficulty of the irradiation method is the temperature rise in the sample during irradiation. Ion currents of several tens of nA can be enough to melt a glass holder as the experience showed. A large increase of the sample temperature during irradiation would anneal defects and increase the diffusion of hydrogen, effects that are not taken into account in the simulations done above. The need of low fluences increases automatically the irradiation time (and costs) for a fixed given fluence. We note that a clear increase of the ferromagnetic signal has been achieved after proton irradiation at 110 K in comparison with similar irradiations done at room temperature [13].

(c) The results of Ref. [23] showed that in general HOPG samples before irradiation show a background ferromagnetic signal. There is no clear experimental evidence that proves that this background is always due to magnetic impurities. The ferromagnetic moment (remanent or at saturation) can be of the order or even larger than the one proton irradiation would produce, see for example Fig. 3. Therefore, the magnetic characterization of the sample before irradiation is unavoidable to obtain the effect produced by the ion-irradiation.

### 2.3. Extrinsic Difficulties

(a) Because at the moment there is no possibility to measure the magnetic moment of a sample in the same irradiation chamber, a minimization of sample handling is necessary. Once the sample is measured before the first irradiation it should be transported to the irradiation chamber and back to the SQUID holder taking care that no additional impurities are introduced. We have designed a sample holder that allows us to measure the magnetic moment of the sample in the SQUID and to fix it inside the irradiation chamber without any changes. We investigated the reproducibility of the magnetic signals and checked that the sample handling, even after irradiating it several times with low fluences and very small spots, does not produce systematic changes in the magnetic signals. Our arrangement provides a reproducibility of $\sim 2 \times 10^{-7}$ emu in the field range $\lesssim 2$ kOe [12] and allows the subtraction of the virgin data from those after irradiation point by point, increasing substantially the sensitivity of the magnetic measurements to $\sim 2 \times 10^{-8}$ emu [13].

(b) SQUID measurements are time consuming. Firstly, one needs several weeks prior to any irradiation to check for the reproducibility of the whole procedure, including the fixing of the sample and the transport to the irradiation chamber. The SQUID sensitivity and reproducibility should assure that changes in the magnetic moment in the range of $\sim 1$ pemu or larger are real and due to the sample changes produced by the irradiation. The commercial SQUID apparatus can also produce some artificial loops due in part to the hysteretic behavior of the superconducting solenoid used to produce the magnetic field and therefore care should be taken with very small ($\lesssim 10^{-7}$ emu) ferromagnetic-like magnetic moment signals.

(c) The last extrinsic difficulty we would like to mention is the needed accelerator time and the estimate of the fluence. As a large scale machine, an accelerator in the MeV range is not always available. Therefore, one tries to minimize the necessary amount of irradiations. Systematic long irradiation procedures, e.g. the study of the change of the magnetic moment vs. fluence or diameter of the micro-spots, etc., are in general difficult to realize by a single research group. The fluence values one provides are nominal ones obtained after measuring the time and the (small) dc ion currents and/or through RBS measurements and simulations. These values might have errors due to current leaks or other electronic artifacts.

### 3. SQUID measurements

Figure 3 shows the remanent magnetic moment (zero external field) of three HOPG samples (two virgin (+) and one irradiated (●)) after magnetizing them with a field of 0.1 T (1 T for the virgin sample (+)) at 300 K and cooling down in field to 5 K. The finite remanence...
as well as the observed irreversibility are clear signs for ferromagnetic behavior. The results of the two virgin HOPG samples (○, +) demonstrate that the magnetic characteristics of nominally identical HOPG samples can be different and stress the necessity of their characterization prior to any irradiation. According to PIXE measurements there are no differences in the magnetic impurity concentration between the three samples shown in Fig. 3. The observed differences should be related to differences in the defect and/or hydrogen concentrations.

Recently published work showed that the magnetization of HOPG samples after proton irradiation at low temperatures and at fields $B \geq 0.1$ T decreases linearly with temperature [13]. This behavior has been interpreted in terms of two-dimensional Heisenberg model with a weak anisotropy. It is interesting to note that the remanence of the virgin HOPG sample shown in Fig. 3 shows also a linear temperature dependence whereas the remanence of the irradiated HOPG sample a sublinear one. These results indicate that the excitation of spin waves in magnetic graphite does not follow the usual 3D Bloch model in agreement with the results of Ref. [13]. Note that both, the irradiated as well as the virgin samples indicate a Curie temperature above 400 K.

At the actual stage of knowledge and due to the narrow window of the values of the irradiation parameters necessary to trigger magnetic order in graphite and the influence of external parameters (sample dimensions, thermalization, etc.) one should not expect high reproducibility between irradiation studies. The CMAM group (Madrid), irradiated different HOPG samples with protons at 3 MeV energy and observed a relatively large increase of the ferromagnetic moment at a fluence $\sim 0.2 \text{nC/}\mu\text{m}^2$ [15]. Because the magnetic moments of the selected virgin samples were notcharacterized before irradiation, no quantitative estimate for the irradiation effect could be done. Xia et al. [21] irradiated HOPG samples with $\text{C}^+$-ions of 70 keV energy obtaining a similar behavior for the ferromagnetic moment vs. fluence as previously observed [9]. They obtained a linear temperature dependence for the remanence of the irradiated samples and estimated a critical temperature of 450 K [21] in agreement with the previously reported behavior [13] and that shown in Fig. 3.

### 4. XMCD results on magnetic spots produced on carbon films

In Ref. [14] the spin dependence of the x-ray absorption was studied in different proton-irradiated spots produced on two different carbon films. The overall results in the two samples indicate that the spin polarization of the pi-electrons leads to magnetic order at the irradiated spots only. The surroundings of the spots, a disordered carbon matrix, is para- or diamagnetic and do not reveal any magnetic dichroism within experimental error at room temperature. The XMCD measurements provide evidence for magnetic order at the irradiated spots given by, for example:

- the observation of magnetic domain patterns. These patterns depend on the graphitized state of the film.
- The appearance of magnetic anisotropy. The contrast observed by XMCD on the partially graphitized film indicate that the magnetization exhibits a preferred alignment parallel to the film surface.
- The quantitative observation of a magnetic moment that cannot be explained by paramagnetism or any of its related phenomena at room temperature.

X-ray absorption at the Carbon K-edge only probes the electronic structure of the 2p final state, because only direct optical transition from 1s core level electrons into 2p final states contribute to the absorption signal. The two main features in the carbon absorption spectra come from the two different types (symmetries) of the s-p-orbitals that are possible and labeled “π” and “σ”. Due to the negligible core-hole interaction in carbon, intermediate excited states are not observed in the K-edge soft x-ray absorption, thus the line shape is only determined by the carbon π-states in the ground state [24].

### 5. Kelvin Probe Microscopy measurements

As discussed above, proton irradiation in graphite samples can produce a ferromagnetic phase in a specific part of the sample interior only. In particular for the case of ferromagnetic spots of micrometer size [12,13,14] the localization of the magnetic part does not allow for an easy characterization of its electrical properties. In order to characterize the electrical properties of these spots Kelvin probe force microscopy measurements on micrometer small magnetic spots have been performed [25]. The results reveal a charge transfer from the center of the spot to an external ring, similar to that observed by XMCD [14]. Scanning transmission X-ray microscopy measurements on similar spots reveal similar charge distribution. The potential variation of the order of 50 mV and its distribution can be well understood in terms of practically unscreened potentials [25] indicating that the magnetic material has insulating properties in agreement with the expectations [5,18].

### 6. Magnetoresistance measurements

A direct, alternative method to detect and study magnetic order is to measure the magnetoresistance (MR). The MR develops a characteristic butterfly loop when measured vs. magnetic field. Additionally, from a ferromagnet we might expect that the MR depends on the orientation of the magnetization with respect to the electric current direction, i.e. the so called Anisotropic MR (AMR). We have prepared a HOPG sample of dimensions $4.4 \times 1 \times 0.01$ mm$^3$ and irradiated it with 12 spots, 0.8 mm diameter each, of 2 MeV protons of nominal
0.1 nC/μm² fluence. Our four-point van der Pauw arrangement and experimental conditions allow us low-noise transport measurements with a relative resolution of ~ 10 ppm in the resistance R.

The non-irradiated HOPG sample showed basically no MR for the parallel-to-the-planes field direction in agreement with earlier results [26]. In that work it was demonstrated that the always positive MR measured for this field direction is directly proportional to the perpendicular field component only. Because our HOPG samples are composed by crystallites with an average deviation angle of ~ 0.4° respect to the nominal c—axis of the sample, a perfectly parallel field to the graphene planes cannot be applied to the whole sample and this is the origin for the small and positive MR.

After irradiation the HOPG sample showed a negative MR and clear hysteresis loops at low temperatures and fields confirming the ferromagnetic state of HOPG after irradiation, see Fig. 4. The irradiated sample had 100 times larger resistivity than in its virgin state and showed a strong negative temperature coefficient indicating a semiconducting-like behavior. Figure 4(a) shows the MR at 25 K at three angles θ between the field and the external input current (θ = 0 means field parallel to the current and the sample main length). The observed behavior as well as the absolute change of the MR is compatible with the AMR effect as, for example, measured in ferromagnetic Co-nanowires [27]. We note that a positive and small $B^2$ contribution to the MR and observable at fields above ~5 T has been subtracted from the data shown in Fig. 4(a).

One may speculate that the AMR observed in the irradiated sample may be due to the paramagnetic state and not to a ferromagnetic state of the sample. Note that paramagnetic anisotropic MR has been observed in, for example, SrRuO$_3$ at 170 K above the corresponding $T_C$ = 150 K [28]. However, several facts appear to rule out this possibility. Measurements at different temperatures indicate that the AMR effect decreases with temperature with a dependence incompatible with a paramagnetic state (note that SQUID measurements show that the paramagnetism produced by irradiation follows the Curie $1/T$ law [12,13,17]). From the AMR data one can estimate the change of the magnetization at saturation $M_s$ assuming that $M_s \propto (MR)^{1/2}$ at high enough fields. The obtained $M_s$ decreases linearly with $T$ in agreement with SQUID results in other, irradiated and non-irradiated ferromagnetic, graphite samples (see Sec. 3). These results indicate a critical temperature $T_C = 190 \pm 10$ K for the sample shown in Fig. 4. Taking the simple model from Ref. [5] and this $T_C$ we expect a distance between vacancies between 2.5 and 3 nm, in fair agreement with the estimated distance in the first 10 μm depth for the nominal fluence, taking into account the errors involved in the Monte Carlo simulations and the lower proton energy used.

There is another experimental fact that speaks against an anisotropic paramagnetic MR. Figure 4(b) shows the hysteresis measured in the MR at low fields and at 4 K for two angles. This behavior indicates ferromagnetic behavior and reflects the micromagnetic state of the sample with the maxima expected at the coercive field $B_C \sim \pm 0.013$ T, in agreement with SQUID results on other irradiated samples.

The remarkable observation of the AMR in irradiated graphite indicates a non-spherical symmetry of the charge distribution and a non-negligible spin-orbit interaction. The anisotropy of the MR should reflect the anisotropy in the electronic wavefunctions [29] but several details have to be clarified in future studies. To answer whether the interfaces between magnetic and non-magnetic regions or only the domain behavior within the magnetic regions play a role, further studies are necessary especially in homogeneously irradiated and thinner HOPG samples.

7. Conclusion

The whole available data indicate that irradiated (as well as some virgin) graphite can show magnetic order above room temperature. The experimental evidence from SQUID, XMCD, transport and to some extent also MFM measurements does not provide any indications that these magnetic signals are related to magnetic impurities. The experimental evidence does not support a (super)paramagnetic state as origin for the observed magnetization effects. Defects appear to play a main role although the question of the influence of hydrogen with or without defects remains still open. Certainly, ion irradiation of graphite is an interesting method to study systematically the influence of defects and its magnetic properties. Systematic transport,
SR, XMCD and NMR studies should be performed in the future to understand the irradiation effects and finally the origin for the observed magnetic order.

On the other hand, the results obtained using a MeV accelerator with all its restrictions and the rather narrow window of parameters to induce magnetic order with large enough amount of sample mass, stress the necessity to search for more comfortable production methods. New possibilities to produce magnetic graphite appeared recently. One is through the irradiation of carbon ions at 70 keV energy. Although the penetration depth of those ions is small (∼ 250 nm) the obtained magnetic signals are high, reaching a magnetization of ∼ 10 emu/g [21]. An alternative, peculiar method to produce magnetic carbon is the one used in Ref. [16] where magnetic carbon powder was produced by a pulsed arc ignited between two carbon electrodes submerged in ethanol, reaching a saturation magnetization of ∼ 1 emu/g. Instead of producing defects in highly oriented graphite samples, other possibility to trigger magnetic order could be to start from a disordered polymer with only C, O and H elements. By annealing one removes O and H graphitizing partially the rest carbon, which matrix remains highly disordered and may have ferromagnetic regions.

References

[1] K. Kusakabe, M. Maruyama, Phys. Rev. B 67 (2003) 092406.
[2] E. J. Duplock, M. Scheffler, P. J. D. Lindan, Phys. Rev. Lett. 92 (2004) 225502.
[3] O. V. Yazyev, L. Helm, Phys. Rev. B 75 (2007) 125408.
[4] H. Kumanaki, D. S. Hirashima, Journal of the Physical Society of Japan 76 (2007) 064713.
[5] L. Pisani, B. Montanari, N. Harrison, New Journal of Physics 10 (2008) 033002.
[6] P. Esquinazi, Handbook of Magnetism and Advanced Magnetic Materials, Vol. 4, John Wiley & Sohn Ltd, Chichester, UK, 2007, pp. 2256–2281.
[7] T. Makarova, B. Sundqvist, R. Höhne, P. Esquinazi, Y. Kopelevich, P. Scharff, V. A. Davydov, L. S. Kashevarova, A. V. Rahamanina, Nature 413 (2001) 716 and its retraction in Nature 440 (2006) 707.
[8] A. Talyzin, A. Dzwilewski, L. Dubrovinsky, A. Setzer, P. Esquinazi, Eur. Phys. J. B 55 (2007) 57.
[9] P. Esquinazi, D. Spemann, R. Höhne, A. Setzer, K.-H. Han, T. Butz, Phys. Rev. Lett. 91 (2003) 237201.
[10] P. O. Lehtinen, A. S. Foster, A. Ayuela, A. Krahenbühl, K. Nordlund, R. M. Nieminen, Phys. Rev. Lett. 91 (2003) 017202.
[11] P. O. Lehtinen, A. S. Foster, Y. Ma, A. Krahenbühl, R. M. Nieminen, Phys. Rev. Lett. 93 (2004) 187202.
[12] J. Barzola-Quiquia, P. Esquinazi, M. Rothermel, D. Spemann, A. Setzer, T. Butz, Nucl. Instrum. Methods Phys. Res. B 256 (2007) 412.
[13] J. Barzola-Quiquia, P. Esquinazi, M. Rothermel, D. Spemann, T. Butz, N. García, Phys. Rev. B 76 (2007) 161403(R).
[14] H. Ohldag, T. Tyliszczak, R. Höhne, D. Spemann, P. Esquinazi, M. Ungureanu, T. Butz, Phys. Rev. Lett. 98 (2007) 187204.
[15] M. A. Ramos, A. Asenjo, M. Jaafar, A. Climent-Font, A. Muñoz-Martínez, J. Camarero, M. García-Hernández, M. Vázquez, Progress in Industrial Mathematics at ECMI 2006, Springer, Berlin-Heidelberg, 2007, pp. 477–482.
[16] N. Parkanska, B. Atterkopa, R. L. Boxman, G. Leitush, O. Berkhe, Z. Barkayd, Y. Rosenberg, N. Eliaz, Carbon 46 (2008) 215.
[17] R. Höhne, P. Esquinazi, V. Heera, H. Weishart, A. Setzer, D. Spemann, J. Magn. Magn. Mater. 320 (2008) 966.
[18] O. V. Yazyev, Phys. Rev. Lett. 101 (2008) 037203.
[19] M. P. López-Sancho, F. de Juan, M. A. H. Vozmediano, arXiv:0806.3900.
[20] R. Höhne, K.-H. Han, P. Esquinazi, A. Setzer, H. Semmelhack, D. Spemann, T. Butz, J. Magn. Magn. Mater. 272-276 (2004) e839.
[21] H. Xia, W. Li, Y. Song, X. Yang, X. Liu, M. Zhao, Y. Xia, C. Song, T.-W. Wang, D. Zhu, J. Gong, Z. Zhu, Adv. Mater. 20 (2008) 1.
[22] J. P. Ziegler, The stopping and range of ions in matter, Pergamon Press, New York, 1977-1985.
[23] P. Esquinazi, A. Setzer, R. Höhne, C. Semmelhack, Y. Kopelevich, D. Spemann, T. Butz, B. Kohlstrunk, M. Lösche, Phys. Rev. B 66 (2002) 024429.
[24] J. Stoehr, H. C. Siegmann, Magnetism - From Fundamentals to Nanoscale Dynamics, Springer Heidelberg, 2006, chapters 9 and 10, pages 351-476.
[25] K. Schindler, N. García, P. Esquinazi, H. Ohldag, Phys. Rev. B 78 (2008) 045433.
[26] H. Kempa, H. C. Semmelhack, P. Esquinazi, Y. Kopelevich, Solid State Commun. 125 (2003) 1.
[27] G. Durnipich, T. P. Krome, B. Hausmanns, J. Magn. Magn. Mater. 248 (2002) 241.
[28] I. Genish, Y. Katz, L. Klein, J. W. Reiner, M. R. Beasley, J. Appl. Phys. 95 (2004) 6681.
[29] H. Ebert, A. Veres, J. Banhart, Phys. Rev. B 54 (1996) 8479.