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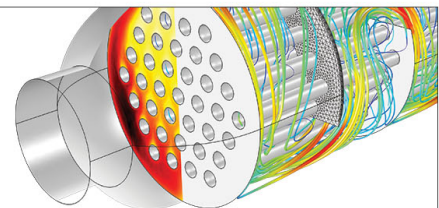
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# Simulation of the enhanced Curie temperature in $\text{Mn}_5\text{Ge}_3\text{C}_x$ compounds

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$\text{Mn}_5\text{Ge}_3\text{C}_x$  films with  $x \geq 0.5$  were experimentally shown to exhibit a strongly enhanced Curie temperature  $T_C$  compared to  $\text{Mn}_5\text{Ge}_3$ . In this letter we present the results of our first principles calculations within Green's function approach, focusing on the effect of carbon doping on the electronic and magnetic properties of the  $\text{Mn}_5\text{Ge}_3$ . The calculated exchange coupling constants revealed an enhancement of the ferromagnetic Mn–Mn interactions mediated by carbon. The essentially increased  $T_C$  in  $\text{Mn}_5\text{Ge}_3\text{C}$  is well reproduced in our Monte Carlo simulations and together with the decrease of the total magnetization is found to be predominantly of an electronic nature. © 2009 American Institute of Physics. [DOI: 10.1063/1.3134482]

Intense efforts have recently been devoted to the fabrication of high- $T_C$  metal/metalloid materials for their potential incorporation into spintronic devices. Among them,  $\text{Mn}_5\text{Ge}_3$  seems to be a promising candidate due to its compatibility with mainstream silicon technology.<sup>1</sup> The low Curie temperature [ $T_C=304$  K (Ref. 2)] of this compound, which is a main disadvantage for technological applications, has recently been overcome by carbon doping in  $\text{Mn}_5\text{Ge}_3\text{C}_x$  films.<sup>3</sup> It was shown<sup>3</sup> that carbon incorporation into the octahedral voids of the hexagonal  $\text{Mn}_5\text{Ge}_3$  cell leads to a continuous increase of  $T_C$  with the doping level in  $\text{Mn}_5\text{Ge}_3\text{C}_x$  and suggests a saturation when all octahedral voids are filled by carbon. A maximum  $T_C$  of 445 K was obtained for  $\text{Mn}_5\text{Ge}_3\text{C}_{0.8}$  films, obtained by magnetron sputtering. The carbon implanted  $\text{Mn}_5\text{Ge}_3\text{C}_{0.8}$  films were found to exhibit magnetic properties very similar to their sputtered counterparts.<sup>4</sup> The average saturated moment of  $2.2\mu_B/\text{Mn}$  was observed for C-implanted  $\text{Mn}_5\text{Ge}_3\text{C}_{0.8}$  films ( $1.1\mu_B/\text{Mn}$  in the sputtered samples) and turned to be somewhat smaller than  $2.6\mu_B/\text{Mn}$  of  $\text{Mn}_5\text{Ge}_3$  polycrystals.<sup>4</sup> At the same time, the isostructural antiferromagnetic (AFM)  $\text{Mn}_5\text{Si}_3$  with  $T_N=98$  K was reported to exhibit ferromagnetism when doped with carbon, with the transition temperature reaching 350 K in  $\text{Mn}_5\text{Si}_3\text{C}_{0.8}$ .<sup>5</sup>

While in  $\text{Mn}_5\text{Si}_3\text{C}_x$  films the interstitial carbon leads to a lattice expansion, the increase of  $T_C$  upon doping in  $\text{Mn}_5\text{Ge}_3\text{C}_x$  is accompanied by a lattice compression.<sup>3</sup> However, it was suggested that the observed lattice distortions in both  $\text{Mn}_5\text{Ge}_3\text{C}_x$  and  $\text{Mn}_5\text{Si}_3\text{C}_x$  can have a very small influence on the increase of the transition temperatures.<sup>3</sup> On the other hand, it was also concluded that the double-exchange mechanism plays only a minor role in enhancing the ferromagnetism in  $\text{Mn}_5\text{Ge}_3\text{C}_x$ . In spite of the existing experimental data on the magnetic properties of C-doped Mn–Ge and Mn–Si compounds, the information about the local magnetic moments, magnetic interactions and the role of carbon interstitials on the enhancement of the  $T_C$  of  $\text{Mn}_5\text{Ge}_3\text{C}_x$  is still lacking. Hence, in this letter we explore possible zero- and finite-temperature magnetic properties and transition temperatures of the pure and C-doped  $\text{Mn}_5\text{Ge}_3$  compounds by first-principles calculations and Monte Carlo simulations.

We follow a standard scheme for the calculation of thermodynamical properties of magnetic systems: (1) first the Green's function formalism and the magnetic force theorem<sup>6</sup> are employed to determine the exchange integrals  $J_{ij}$  from first principles; (2) these are used as input to a classical Heisenberg Hamiltonian of the form  $H=-\sum_{i,j;i \neq j} J_{ij} \vec{e}_i \cdot \vec{e}_j$ , where  $i$  and  $j$  are the site indexes and  $\vec{e}_i$  is a unit vector along a spin moment at  $i$ . The  $T_C$  is estimated from the peak in susceptibility-temperature curve, obtained by Monte Carlo simulations using 2160 magnetic-atom supercells. The *ab initio* calculations are performed by the full-potential screened Korringa–Kohn–Rostoker (KKR) Green function method<sup>7</sup> within the local spin density approximation<sup>8</sup> of density functional theory. For structural relaxation we use the projector-augmented wave approach as implemented in the ABINIT code,<sup>9</sup> within the generalized gradient approximation for the exchange-correlation energy.<sup>10</sup>

The unit cell of the hexagonal  $\text{Mn}_5\text{Ge}_3$  (space group  $P6_3/mcm$ ,  $D8_8$ -type structure<sup>11</sup>) contains two sublattices of Mn ( $\text{Mn}_I$  and  $\text{Mn}_{II}$ ) with different coordination. The crystal-line structure of the  $\text{Mn}_5\text{Ge}_3\text{C}_x$  (Fig. 1) was found to be similar to the  $\text{Mn}_5\text{Ge}_3$  structure with carbon atoms occupying interstitial positions at the center of  $\text{Mn}_{II}$  octahedron.<sup>3</sup> In order to study the effect of hybridization and structural relaxations, we performed calculations for: (i) *rigid* (nonrelaxed)  $\text{Mn}_5\text{Ge}_3$  structure at the experimental atomic positions and lattice parameters  $a=7.184$  Å and  $c/a=0.703$ ;<sup>11</sup> (ii) *relaxed*  $\text{Mn}_5\text{Ge}_3$  with atomic positions optimized at the fixed lattice parameters, used in (i); (iii) rigid  $\text{Mn}_5\text{Ge}_3\text{C}$ , where

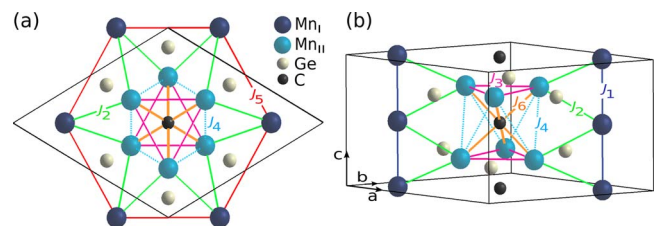


FIG. 1. (Color online) Crystal structure and exchange coupling scheme for the carbon-interstitial phase  $\text{Mn}_5\text{Ge}_3\text{C}_x$  at  $x=1$  (full occupancy of carbon): (a) projection on  $xy$ -plane and (b) side view. Colored spheres denote Ge (gray),  $\text{Mn}_I$  (dark blue),  $\text{Mn}_{II}$  (light blue), and interstitial C (black) at the center of  $\text{Mn}_{II}$  octahedra. Important exchange parameters for different Mn–Mn distances are shown in different colors. The black line indicates the edges of the unit cell.

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TABLE I. Local and total magnetic moments (in  $\mu_B$ ), compared with experimental data where possible.

System	$\mu_{\text{Mn}_I}$	$\mu_{\text{Mn}_{II}}$	$\mu_{\text{Ge}}$	$\mu_{\text{C}}$	$\mu_{\text{tot}}$
Mn <sub>5</sub> Ge <sub>3</sub> (rigid)	2.09	3.15	−0.15		26.37
Mn <sub>5</sub> Ge <sub>3</sub> (relaxed)	2.11	3.11	−0.14		26.25
Exp. <sup>a</sup>	1.96	3.26			26
Mn <sub>5</sub> Ge <sub>3</sub> C (rigid)	2.21	2.37	−0.14	−0.26	21.72
Mn <sub>5</sub> Ge <sub>3</sub> C (relaxed)	1.99	2.14	−0.13	−0.21	19.59
Exp. <sup>b</sup> /Exp. <sup>c</sup>	1.1/2.2	1.1/2.2			11/22

<sup>a</sup>Reference 12.<sup>b</sup>Reference 3.<sup>c</sup>Reference 4.

two C atoms are inserted into the interstitial sites of the rigid Mn<sub>5</sub>Ge<sub>3</sub> cell; and (iv) relaxed Mn<sub>5</sub>Ge<sub>3</sub>C with the coordinates optimized at the fixed lattice parameters  $a=7.135$  Å and  $c/a=0.700$  of the Mn<sub>5</sub>Ge<sub>3</sub>C<sub>0.75</sub> films.<sup>3</sup>

According to neutron scattering experiments,<sup>12</sup> the difference in local environment of Mn<sub>I</sub> and Mn<sub>II</sub> atoms in Mn<sub>5</sub>Ge<sub>3</sub> is believed to be responsible for the different magnetic moments on them (Table I). The smaller magnetic moment on Mn<sub>I</sub> is due to a direct Mn<sub>I</sub>–Mn<sub>I</sub> interaction at a rather short distance (2.526 Å).<sup>12</sup> The obtained values agree well with the previous calculations<sup>1,13</sup> and experimental observations.<sup>12</sup> The electronic density of states (DOS) (Fig. 2) is metallic, in agreement with the recent calculations.<sup>1</sup> The partial DOS of Mn atoms is dominated by the 3d-states, while the largest contribution to Ge DOS is due to 4p- and 4s-states. The DOS at the Fermi level ( $E_F$ ) is dominated by the Mn d-states, pointing at the significant Mn–Mn interaction.<sup>1</sup> The exchange splitting is larger for Mn<sub>II</sub> d-states compared to Mn<sub>I</sub>, in agreement with the larger magnetic moment on Mn<sub>II</sub>.

In order to understand the role of C doping in the enhancement of  $T_C$ , we first calculated the rigid Mn<sub>5</sub>Ge<sub>3</sub>C unit

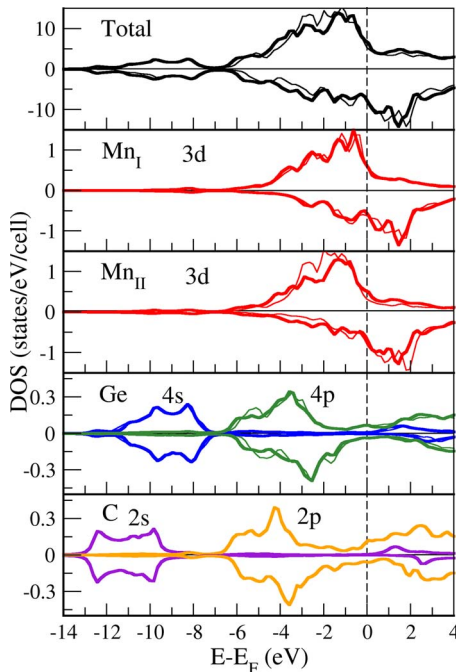


FIG. 2. (Color online) Spin-resolved total and atom-projected DOS, calculated within the KKR method, for the Mn<sub>5</sub>Ge<sub>3</sub> (thin line) and Mn<sub>5</sub>Ge<sub>3</sub>C (thick line) phases in FM configuration. Note the additional fine structure in the DOS of Mn<sub>I</sub> for Mn<sub>5</sub>Ge<sub>3</sub>C due to Mn–C hybridization.

cell with two carbon atoms in the octahedral voids and compared it to the corresponding results for the undoped compound. Such situation represents the pure hybridization effect between the carbon and the neighboring Mn<sub>II</sub> atoms. As it follows from Fig. 2, carbon incorporation into Mn<sub>5</sub>Ge<sub>3</sub> essentially changes the 3d-states of Mn<sub>II</sub>, leaving the corresponding Mn<sub>I</sub> states almost unaffected. The hybridization between the C 2p- and Mn<sub>II</sub> 3d-states leads to a shift of the main occupied peaks in the majority, as well as unoccupied peaks in the minority 3d DOS of Mn<sub>II</sub> toward  $E_F$ , consequently increasing the DOS  $N(E_F)$  at the  $E_F$  in both spin channels. The exchange splitting is now lower than in the pure Mn<sub>5</sub>Ge<sub>3</sub>, resulting in a reduced magnetic moment on Mn<sub>II</sub>. The magnetic moment of the cell (Table I) is mainly contributed by the Mn<sub>I</sub> and Mn<sub>II</sub> atoms, while the induced magnetic moments on Ge and C are much smaller and are antiparallel to the moments on Mn. The structure relaxations caused by interstitial atoms decrease the interatomic Mn–Mn distances (Table II), slightly reducing the magnetic moments. However, the effect of hybridization on the decrease of the total magnetization is much larger than the effect of relaxation. This conclusion follows from our electronic structure calculations for the relaxed Mn<sub>5</sub>Ge<sub>3</sub>C system with the empty spheres at carbon positions (further referred to as Mn<sub>5</sub>Ge<sub>3</sub>V<sub>C</sub>). The calculated magnetic moments on Mn agree well with the average saturated moment of  $2.2\mu_B/\text{Mn}$ , observed for the C-implanted Mn<sub>5</sub>Ge<sub>3</sub>C<sub>0.8</sub> films,<sup>4</sup> but deviate from those obtained for the sputtered samples, where the largest moment of  $1.1\mu_B/\text{Mn}$  was observed for Mn<sub>5</sub>Ge<sub>3</sub>C<sub>0.75</sub>.<sup>5</sup> This discrepancy could be ascribed to disorder effects and defects formation, which may differ in sputtered and implanted samples.

In Table II we present some of the important calculated exchange constants for the relaxed and rigid Mn<sub>5</sub>Ge<sub>3</sub> and Mn<sub>5</sub>Ge<sub>3</sub>C systems (see Fig. 1 on the notation). Only the interactions between Mn spins are shown, as Mn–Ge interactions turned to be negligibly small. The first nearest neighbor Mn<sub>I</sub>–Mn<sub>I</sub> interactions  $J_1$  (at the shortest distance of 2.526 Å) are ferromagnetic (FM) and clearly dominate over the corresponding Mn<sub>I</sub>–Mn<sub>II</sub> and Mn<sub>II</sub>–Mn<sub>II</sub> interactions, confirming the assumption about the different magnitude of exchange interaction for Mn atoms in different sublattices.<sup>14</sup> The dependence of the exchange parameters on the interatomic distances is stronger for the Mn<sub>II</sub> sublattice, while it is weaker for the Mn<sub>I</sub> one. As it follows from Table II, in Mn<sub>5</sub>Ge<sub>3</sub> there is an AFM  $J_3$  interaction between the Mn<sub>II</sub> atoms within  $z=\frac{1}{4}$  and  $z=\frac{3}{4}$  planes (perpendicular to the  $c$ -axis), and FM  $J_4$  and  $J_6$  interactions between Mn<sub>II</sub> belonging to different planes. The negative sign for  $J_3$  could be responsible for the small degree of noncollinearity in Mn<sub>5</sub>Ge<sub>3</sub>, observed in the previous first-principles calculations.<sup>13</sup> However, an increase of the corresponding Mn<sub>II</sub>–Mn<sub>II</sub> distance from 2.974 to 3.057 Å after structure relaxation leads to the change from AFM to FM  $J_3$  parameter, while the rest of the parameters are left almost unchanged. As a result the estimated value of the  $T_C=400$  K for the relaxed Mn<sub>5</sub>Ge<sub>3</sub> system is somewhat higher than for the rigid one of 320 K and than the corresponding experimentally observed value of 304 K.<sup>2</sup>

+The results presented in Table II show that interstitial carbon, even without relaxation, significantly changes the value of  $J_2$ ,  $J_3$ , and  $J_6$ , leaving the  $J_4$  and  $J_1$  interactions



TABLE II. Calculated (within KKR) exchange constants  $J_{ij}$  and  $T_C$  for the rigid and relaxed  $\text{Mn}_5\text{Ge}_3$  and  $\text{Mn}_5\text{Ge}_3\text{C}$  compounds. The corresponding Mn–Mn distances (in Å) are shown in square brackets. Positive (negative) values characterize FM (AFM) coupling. Results for  $\text{Mn}_5\text{Ge}_3\text{V}_\text{C}$  are presented to distinguish between the structural and chemical effects of doping.

$J_{ij}$ (mRy)	$\text{Mn}_5\text{Ge}_3$ (rigid)	$\text{Mn}_5\text{Ge}_3$ (relaxed)	$\text{Mn}_5\text{Ge}_3\text{C}$ (rigid)	$\text{Mn}_5\text{Ge}_3\text{C}$ (relaxed)	$\text{Mn}_5\text{Ge}_3\text{V}_\text{C}$
$J_1^{\text{Mn}_\text{I}-\text{Mn}_\text{I}}$	+2.14 [2.526]	+2.09 [2.527]	+2.24 [2.526]	+2.34 [2.498]	+2.24 [2.498]
$J_2^{\text{Mn}_\text{I}-\text{Mn}_\text{II}}$	+0.59 [3.068]	+0.59 [3.039]	+0.90 [3.068]	+0.69 [3.124]	+0.40 [3.124]
$J_3^{\text{Mn}_\text{II}-\text{Mn}_\text{II}}$	−0.15 [2.974]	+0.13 [3.057]	+0.84 [2.974]	+0.51 [2.714]	−1.80 [2.714]
$J_4^{\text{Mn}_\text{II}-\text{Mn}_\text{II}}$	+0.51 [3.055]	+0.52 [3.082]	+0.44 [3.055]	+0.60 [2.948]	+0.28 [2.948]
$J_5^{\text{Mn}_\text{I}-\text{Mn}_\text{I}}$	−0.10 [4.148]	−0.06 [4.148]	−0.16 [4.148]	−0.22 [4.118]	−0.09 [4.118]
$J_6^{\text{Mn}_\text{II}-\text{Mn}_\text{II}}$	+0.69 [4.263]	+0.65 [4.341]	+0.07 [4.263]	+0.22 [4.008]	+0.76 [4.008]
$T_C$ (K)	320	400	430	450	spin-disordered

almost unaffected. In particular, the  $J_3$  interaction becomes strongly FM compared to the undoped  $\text{Mn}_5\text{Ge}_3$ . According to the DOS of  $\text{Mn}_5\text{Ge}_3\text{C}$  in Fig. 2, this increase of the FM interaction can probably be explained by the strong  $p$ - $d$  hybridization between  $\text{Mn}_\text{II}$  and C states, which enhances the hopping of the  $3d$  electrons from the partially occupied  $d$ -states of one  $\text{Mn}_\text{II}$  atom to a  $3d$  orbital of the neighboring  $\text{Mn}_\text{II}$ . The  $J_6$  parameter, which in the doped compound corresponds to the  $180^\circ$   $\text{Mn}_\text{II}$ –C– $\text{Mn}_\text{II}$  interaction (thick orange line on Fig. 1), is essentially lower than the corresponding direct  $\text{Mn}_\text{II}$ – $\text{Mn}_\text{II}$  exchange in the parent compound, pointing to the possible superexchange interaction between  $\text{Mn}_\text{II}$  via carbon, as predicted by Goodenough–Anderson–Kanamori (GAK) rules.<sup>15</sup> According to these,  $90^\circ$   $\text{Mn}_\text{II}$ –C– $\text{Mn}_\text{II}$  interactions should be FM, which is the case for  $J_3$  and  $J_4$ . In this model interatomic exchange constants are strongly dependent on the orbital overlap, and hence sensitive to changes in the interatomic distances. Because of this  $J_3$  and  $J_4$  parameters, corresponding to different  $\text{Mn}_\text{II}$ – $\text{Mn}_\text{II}$  distances, change differently upon C-doping. In addition, there are two simultaneous  $90^\circ$  superexchange paths through C at  $z=0$  and  $z=\frac{1}{2}$  planes, which contribute to  $J_3$  interaction (see Fig. 1). In contrast,  $J_4$  coupling is associated with the only possible  $\text{Mn}_\text{II}$ –C– $\text{Mn}_\text{II}$  superexchange path and is probably influenced by the interactions through  $\text{Mn}_\text{II}$ – $\text{Mn}_\text{I}$ – $\text{Mn}_\text{II}$  bridge. It should be noted that GAK rules have also been applied to explain the first-order FM-to-AFM transition in  $\text{Mn}_3\text{GaC}_{1-\delta}$  antiperovskite compounds,<sup>16</sup> in which the local environment of Mn atoms is similar to that in  $\text{Mn}_5\text{Ge}_3\text{C}$ .

The transition temperature, calculated using the exchange parameters for the rigid C-doped system, is essentially higher ( $T_C=430$  K) than in the undoped compound. This is a direct indication that the strongly enhanced FM stability is not related solely to the variation of the Mn–Mn interatomic distances. To distinguish the effect of relaxations from the electronic structure effect on the enhanced FM interaction in  $\text{Mn}_5\text{Ge}_3\text{C}$ , we compared the values of the exchange parameters in the  $\text{Mn}_5\text{Ge}_3\text{V}_\text{C}$  with those calculated for the parent compound. We can conclude that the essential decrease of the  $\text{Mn}_\text{II}$ – $\text{Mn}_\text{II}$  distances due to carbon insertion reduces the FM exchange interaction, and has a particular influence on  $J_3$  making it strongly AFM, thus destabilizing the collinear magnetic structure in  $\text{Mn}_5\text{Ge}_3\text{V}_\text{C}$  (Table II). The relaxation makes  $J_3$  in  $\text{Mn}_5\text{Ge}_3\text{C}$  somewhat lower, but still high compared to that in the pure compound. The  $J_4$  parameter is higher in relaxed  $\text{Mn}_5\text{Ge}_3\text{C}$ , pointing to the  $90^\circ$  FM

superexchange enhanced by the corresponding distance decrease. Although the strong hybridization between Mn  $3d$  and C  $2p$  orbitals leads to the contraction of the interatomic distances and lowers the longer-distance exchange constants, the FM Mn–Mn interactions prevail in the  $\text{Mn}_5\text{Ge}_3\text{C}$ , thus giving larger contribution to the  $T_C$  than the AFM ones. The calculated  $T_C=450$  K is only 20 K larger than in the nonrelaxed  $\text{Mn}_5\text{Ge}_3\text{C}$ , pointing to the small effect of the structural distortions on the  $T_C$  increase in  $\text{Mn}_5\text{Ge}_3$  due to C-doping. The obtained value is in a very good agreement with the maximum value of the experimentally measured  $T_C$  of 445 K.<sup>3,4</sup> To summarize, the present studies clarified that the enhanced FM stability of C-doped  $\text{Mn}_5\text{Ge}_3$  compounds is attributed to the appearance of the  $90^\circ$  FM superexchange between Mn atoms mediated by carbon, while the structural distortions are found to be a secondary effect.

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