Enhanced magnetism and time-stable remanence at the interface of hematite and carbon nanotubes

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Abstract
The interface of two dissimilar materials is well known for surprises in condensed matter, and provides avenues for rich physics as well as seeds for future technological advancements. We present some exciting magnetization ($M$) and remanence ($\mu$) results, which conclusively arise at the interface of two highly functional materials, namely the graphitic shells of a carbon nanotube (CNT) and $\alpha$-Fe$_2$O$_3$, a Dzyaloshinskii–Moriya interaction driven weak ferromagnet (WFM) and piezomagnet (PzM). We show that the encapsulation inside a CNT leads to a significant enhancement in $M$ and correspondingly in $\mu$, a time-stable part of the remanence, exclusive to the WFM phase. Up to 70\% of in-field magnetization is retained in the form of $\mu$ at room temperature. The lattice parameter of the CNT around the Morin transition of the encapsulate exhibits a clear anomaly, confirming the novel interface effects. Control experiments on bare $\alpha$-Fe$_2$O$_3$ nanowires bring into the fore that the weak ferromagnets such as $\alpha$-Fe$_2$O$_3$ are not as weak, as far as their remanence and its stability with time is concerned, and encapsulation inside a CNT leads to a substantial enhancement in these functionalities.

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(Some figures may appear in colour only in the online journal)

1. Introduction
Hematite (or $\alpha$-Fe$_2$O$_3$) is an earth abundant and environment-friendly oxide, generally considered as a menace, for its appearance as common rust over elemental Fe, but technologically, it is well known for a very diverse range of applications [1]. However, the observation of weak ferromagnet (WFM) [2, 3] nearly six decades ago in hematite and its connection to spin–orbit coupling (SOC) has had profound implications in the field of spintronics. A variety of non-trivial topological spin structures in chiral magnets stabilizing through Dzyaloshinskii–Moriya interaction (DMI)/SOC have triggered new research areas such as antiferromagnetic (AFM) spintronics and spin orbittronics [4–9].

Generation of WFM in $\alpha$-Fe$_2$O$_3$ is due to a slight canting of its inherent AFM sublattice [2, 3] which persists from 950 K ($T_N$) down to 265 K, well-known Morin transition temperature ($T_M$). Below $T_M$, the spins turn from ‘$a$’ axis to ‘c’ axis (rhombohedral unit cell in hex setting) and the canting vanishes for hematite. Many of such canted AFM, either DMI driven or systems in which canting takes place due to other mechanism, are also known to exhibit the phenomenon of
piezomagnetism [10–14]. Here, piezomagnet (PzM) implies that magnetization can be tuned by stress alone. Another important point is the occurrence of WFM which is concurrent with PzM as theoretically predicted [10] and experimentally observed [11–14]. Dzyaloshinskii also showed that the spin canting effect is larger for compounds with smaller $T_N$ [2]. Thus, WFM/PzM is seen to be the weakest in $\alpha$-Fe$_2$O$_3$ with $T_N \approx 950$ K as compared to MnCO$_3$ or NiCO$_3$ ($T_N$ below 50 K).

This work centers around remanence, which, in general, is an important parameter for any magnetic material for a variety of practical applications related to permanent magnets, soft or hard, relate to this quantity [15–17]. In addition, it is an important tool for probing fundamental magnetic interactions in conventional long range order (LRO) as well as complex magnetic systems, including frustrated, nano and core–shell magnets [17–20]. These systems are better identified by simple remanence measurements, which carry crucial information about the underlying magnetic interaction associated with each of these distinct phases. Recently, we have explored magnetization and remanence in a number of DMI driven WFM and PzM using Superconducting Quantum Interface Device (SQUID) magnetometry [21]. The key result there is the observation of highly time-stable remanence along with some other features that exclusively connect it to WFM phase [21].

Another relevant aspect here is that, magnetic oxides such as hematite are well known to exhibit a remarkably wide range of functional properties [22, 23], device fabrication still remains a challenge due to a number of practical issues. In this light, the oxide encapsulation inside carbon nanotubes (CNTs) is potentially beneficial for a number of reasons. Owing to a wide diversity in the electronic and magnetic ground states of the encapsulate [22–30] together with unprecedented mechanical, electrical and thermal properties of the CNT [24], these hybrids are potential candidates for novel interface effects [25–28]. In this work, we present experimental results that indicate that encapsulation of $\alpha$-Fe$_2$O$_3$ inside a CNT is the most efficient way to enhance the magnitude of time-stable remanence, which is related to the DMI driven WFM and PzM.

## 2. Experimental techniques

### 2.1. Sample preparation

The parent sample for the formation of $\alpha$-Fe$_2$O$_3$@CNT is Fe@CNT. This sample has been synthesized in aligned forest morphology by chemical vapor deposition and the detailed synthesis conditions have been discussed in [31]. The Fe@CNT is suitably annealed to form $\alpha$-Fe$_2$O$_3$@CNT as well as the oxide template discussed in the present work. The annealing conditions for these two samples are described below.

1. **$\alpha$-Fe$_2$O$_3$@CNT**: the as-prepared Fe@CNT is converted into $\alpha$-Fe$_2$O$_3$@CNT by annealing under carbon dioxide atmosphere at 500°C for 20 min. The time and temperature of annealing crucially affect the graphitic shells of a CNT and more importantly, its interface with the oxide encapsulate. The magnitude of enhanced magnetization and the remanence also depends on the parameters such as annealing temperature and time.

### 2.2. Characterization techniques

The Fe@CNT samples have been annealed using a Nabertherm R 100/750/13 furnace to form the oxide@CNT as well as the template. Scanning electron microscope (SEM) images have been acquired using ZEISS ULTRA plus field-emission SEM. High-resolution transmission electron microscope (TEM) images have been obtained using FEI-TECNAL microscope at an operating voltage of 200 kV. The temperature variation of synchrotron x-ray diffraction from 20 to 300 K has been conducted in BL-18 beamline, Photon factory, Japan. The synchrotron data have been fitted using Rietveld profile refinement [32]. The bulk magnetization measurements have been performed using SQUID magnetometer from quantum design.

### 2.3. Magnetization measurement protocol: field cooled (FC) and zero field cooled (ZFC)

The magnetization ($M$) as a function of temperature ($T$) measurements in presence of a fix magnetic field ($H$) have been taken in routine ZFC and FC cycles. The corresponding $M$ has been referred as $M_{ZFC}$ and $M_{FC}$ respectively in the text.

### 2.4. Remanence measurement protocol: FC and ZFC

The remanent state has been prepared following either of the two protocols: (i) sample is cooled in the presence of $H$ from 300 K up to 5 K. The $H$ is switched off at 5 K. The corresponding remanence as a function of time is measured, while temperature is held constant at 5 K. The remanent state in this case, is hence prepared using the FC protocol. (ii) Sample is heated in presence of $H$ from 5 K up to 300 K. The $H$ is switched off at 300 K. Hereafter, the remanence as a function of time is measured while temperature is held constant at 300 K. The remanent state in this case, is hence prepared using the ZFC protocol. It is to be emphasized that the remanence is strictly measured in $H = 0$ condition in either of the protocols. The $H$ indicated in all the figures pertaining to remanence is to convey its magnitude while preparing a remanent state.
3. Results and discussion

Figures 1(a), (b) displays SEM images of the sample α-Fe₂O₃@CNT. Figure 1(a) shows a broad area SEM image, depicting aligned forest morphology of this sample. The presence of α-Fe₂O₃ within the core cavity of a CNT is also evident from the high resolution TEM image (figure 1(c)), depicting the well-formed graphitic shells of the CNT and the oxide encapsulate. The presence of α-Fe₂O₃ and the graphitic phase (CNT) is further confirmed by synchrotron XRD (blue dots) shown in figure 1(g). It is to be noted that neither ferromagnetic Fe nor any other oxides (such as magnetite, etc) could be detected in the synchrotron XRD for this sample. Figures 1(d)–(f) depicts the morphology of the α-Fe₂O₃-template through SEM images. As evident from figure 1(h), the synchrotron XRD data on the template reflect peaks corresponding to α-Fe₂O₃. No peak corresponding to the graphitic phase could be detected in the template. Both type of samples are further characterized by measuring $M$–$H$ isotherms at 300 K, depicting that the encapsulation of hematite inside a CNT (blue dots) leads to a very significant enhancement in the magnitude of $M$, as compared to the template (figure 2). It is also to be noted that the magnitude of magnetization in the given magnetic field range for the oxide-template is consistent with the previous report on nano particles of hematite [21, 33, 34].

3.1. Enhanced magnetization in α-Fe₂O₃@CNT

Magnetization as a function of temperature for α-Fe₂O₃@CNT in typical FC (blue dots) and ZFC (black dots) cycles, measured at $H \sim 1$ kOe is shown in figure 3(a). The same is shown for the α-Fe₂O₃ template in figure 3(b). Both the samples exhibit well pronounced $T_M$, intrinsic to the bulk α-Fe₂O₃. The shift in $T_M$ towards lower temperatures (as compared to bulk α-Fe₂O₃) as well as the functional form of $M$ versus $T$ is consistent with the fact that α-Fe₂O₃ in both cases is in the form of nano wires. Thus, the broad features of magnetization and history effects (i.e. bifurcation in FC/ZFC cycles) can be attributed to nano scaling, which is consistent with previous reports [33, 34]. In conventional LRO or in complex magnetic systems $M_{FC} > M_{ZFC}$ is a frequently observed phenomenon [17, 35]. However, we observe the opposite, especially in the
temperature region above $T_M$ (figures 3(a) and (b)). This is not a common occurrence, but has been reported earlier [36, 37]. We shall come back to this issue in the latter part of the text.

The more prominent observation is about an order of magnitude enhancement in $M$ between $\alpha$-Fe$_2$O$_3$@CNT and the $\alpha$-Fe$_2$O$_3$ template at each $H$. For instance, $M_{FC} = 1.3$ emu g$^{-1}$ (figure 3(a)), whereas it is $\sim 0.1$ emu g$^{-1}$ for the template (figure 3(b)) for $H = 1$ kOe and $T = 5$ K. Assuming that the graphitic shells of a CNT do not contribute magnetically in a conventional sense, the data presented in figures 3(a) and (b) are intriguing. The enhancement is observed at all fields for $\alpha$-Fe$_2$O$_3$@CNT as compared to the template (figure S1 is available online at stacks.iop.org/NANO/30/385706/mmedia). It is to be noted that for the template, the magnitude of $M$ is similar to what one usually observes in $\alpha$-Fe$_2$O$_3$ nano particles [21, 33, 34]. If this enhancement in $M$ was arising only due to the nano scaling of $\alpha$-Fe$_2$O$_3$ or if it was morphology related (aligned forest), the effect should have persisted in the template. Though, both the size effects and morphology certainly have a role to play as far as WFM is concerned [21, 28], data presented in figures 3(a), (b) suggest that the significant enhancement in $M$ is related to the interface effects.

### 3.2. Enhanced remanence in $\alpha$-Fe$_2$O$_3$@CNT

A more striking (and useful) result is the observation of a time-stable remanence measured at 300 K for both the samples. The magnitude of remanence is substantially enhanced in case of $\alpha$-Fe$_2$O$_3$@CNT. As evident from figure 4(a) the magnitude of remanence is at least an order of magnitude larger for $\alpha$-Fe$_2$O$_3$@CNT (blue dots) than what is observed for the template (red dots). Figure 4(b) compares remanence prepared at three different $H$ for $\alpha$-Fe$_2$O$_3$@CNT to depict its stability with time and its counter-intuitive $H$ dependence. As evident from the $M$–$H$ isotherm shown in figure 2 that the magnetization increases with increasing $H$ for both the samples. However, the remanence exhibits a counter-intuitive $H$ dependence. Similar features are observed in remanent state prepared following a FC protocol: the magnitude of remanence ($\sim 0.3$ emu g$^{-1}$) at 5 K is substantially larger (figure 4(c)) as compared to the template ($\sim 0.01$ emu g$^{-1}$) (figure 4(d)), at 5 K. It is also intriguing to note that the remanence is larger and more stable at 300 K than at 5 K, even though thermal fluctuations should disrupt the remanence more at higher temperatures. Thus, it is evident that the magnetization dynamics in these samples is unusual.

### 3.3. Weak ferromagnetism and unusual magnetization dynamics

Recently, investigating remanence in a number of such canted AFM has enabled an understanding that these systems leave
some unique footmarks in remanence. These features are not evident in routine \( M \) versus \( T \) or \( M \) versus \( H \) cycles \([21]\). With special focus on \( \alpha\text{-Fe}_2\text{O}_3 \), which shows both AFM and WFM phase across \( T_M \), the spin configuration is schematically shown for pure AFM (figure 4(e)) and the WFM phase (figure 4(f)), for which the spontaneous canting of the type \( \bar{D} (S_x \times S_y) \) is symmetry allowed, leading to a net ferromagnetic moment in an otherwise AFM. It is to be recalled that the net in-field magnetization in an AFM depends on the energies including Zeeman, exchange and magnetocrystalline anisotropy \([15]\). In the case of WFM, the direction of net ferromagnetic moment due to the canted spins is an additional factor. In the light of above scenario, we discuss all the unusual results, the nature of FC/ZFC bifurcation in \( M \) versus \( T \), the presence of a time-stable remanence with a counter intuitive \( H \) dependence and enhanced magnitude of \( M \) and remanence in case \( \alpha\text{-Fe}_2\text{O}_3@CNT \).

We first discuss the unusual history effects, \( M_{FC} < M_{ZFC} \) (figures 3(a) and (b)). This feature is extremely sensitive to the exact sequence in which FC/ZFC runs are recorded for a particular \( H \) (Text S1). The spin canting in hematite starts from \( T_M \) and persisting right up to 960 K, wherein a WFM to paramagnetic transition occurs. Considering spin configuration of WFM state from figure 4(f), it is clear that the direction of net FM moment associated with a canted AFM domain can be best modulated (w.r.t. the direction of \( H \) if \( H \) is applied from below \( T_M \), just before the spin reorientation transition takes place for \( \alpha\text{-Fe}_2\text{O}_3 \) (i.e. at the onset of spontaneous canting), leading to the larger \( M_{ZFC} \). On the other hand, when \( H \) is applied from above the \( T_M \), where spins are already spontaneously canted (with a net ferromagnetic moment), and their contribution to the total magnetization is not entirely dictated by \( H \). This is because it may not be energetically favorable for small \( H \) to flip the direction of a WFM domain with net ferromagnetic moment pointing in unfavorable direction with respect to applied \( H \). It is also to be emphasized that all routine \( H \) driven process simultaneously exist as they do for any normal AFM under the influence of \( H \). However, the canting is spontaneous, and therefore once the magnetization state is prepared by an in-field cooling (or heating) cycle, as long as history effects are not wiped off by heating the sample above AFM to paramagnetic transition (~950 K), an ambiguity in the data (of the order of differences in FC/ZFC) is likely to exit. This also depends on the
magnitude of $H$ used in the previous run, due to the presence of time-stable remanence. Similar features are observed in bare hematite nano particles prepared by hydrothermal route [49].

### 3.4. Time-stable remanence in canted antiferromagnet

As we have recently shown, manifestation of canting appears in the form of time-stable remanence with a functional form, which is evidently different from other physical mechanisms [21, 28, 49]. From the measurements conducted on single crystal $\alpha$-Fe$_2$O$_3$, we found that this time-stable remanence appears in WFM region and vanishes in pure AFM region, and the effect is also significantly tunable by nano scaling [21]. More importantly, while $M$ increases with increasing $H$, the corresponding remanence exhibits a peak like behavior with increasing $H$ [21, 49]. In case of remanent state prepared following a FC or ZFC cycle, the net magnetization depends on the Zeeman energy as well as the contribution of average net FM moment corresponding to the spontaneously canted WFM domains in the direction of $H$. If the remanent state is prepared with $H$ above a critical value, the Zeeman energy dominates. In this case, after switching off $H$, the remanence decays instantaneously. Between the two extremes, magnetization dynamics is governed by net FM contribution from spontaneously canted spins and the Zeeman Energy. This leads to a peak like pattern in $H$ dependence of time-stable remanence as we have observed in a number of canted AFM [21]. We have also shown experimentally that once a remanent state is set due to $H$ applied in a certain direction, removing $H$ or reversing its direction in WFM region does not alter the magnitude or the direction of remanence [21]. The robustness of this remanence is indicative of WFM domains in the direction of $H$ and flipping its direction would mean flipping of super exchange driven AFM sublattice, which is highly energetically unfavorable [11]. This also explains the time-stable character of remanence.

Thus, the presence of this time-stable remanence exclusively associated with canting explains the ambiguity in magnitude of $M$ (and PzM) on repeated cooling [13, 38] and the importance of the exact sequence in which FC/ZFC runs are recorded (figure S1). The above discussion holds true for both the type of samples presented in this work. Taking into account all these factors, we put an upper limit to the ambiguity related with the magnitude of $M$, which can be $\sim 0.1$–$0.2$ emu g$^{-1}$ in case of template or bare $\alpha$-Fe$_2$O$_3$ nano particles reported earlier [21, 49].

From figure 4(a), it is also evident that both the samples are governed by similar physical process, as the data for $\alpha$-Fe$_2$O$_3$@CNT is a scaled version of the template. However, for the observation of about order of magnitude enhancement in the magnitude of $M$ as well as remanence in $\alpha$-Fe$_2$O$_3$@CNT cannot be explained by the ambiguity related to heating/cooling protocols which is typically $\sim 0.1$ emu g$^{-1}$, as estimated from the difference ($M_{FC}$–$M_{ZFC}$) as estimated from FC/ZFC cycles at any fixed $H$ (figure 4). Thus, the enhancement in $M$ as observed in the $\alpha$-Fe$_2$O$_3$@CNT as compared to the template is much larger than what can be explained by history effects. Therefore, we conclude that the enhancement in magnitude of $M$ and correspondingly remanence in $\alpha$-Fe$_2$O$_3$@CNT is not fully due to either nano scaling (both contain nano wires of $\alpha$-Fe$_2$O$_3$) or morphology of $\alpha$-Fe$_2$O$_3$ (which is quite similar in both samples). This prompted us to explore the oxide/CNT interface and associated strain effects arising due to lattice mismatch in more details.

### 3.5. Temperature variation of lattice parameters across $T_M$

We have recently shown the correlation between structural parameters and the magnitude of remanence for a number of symmetry allowed DMI driven canted AFMs [21]. The $c/a$ ratio also exhibits a much rapid fall with decreasing temperature in case of MnCO$_3$, (which has a relatively lower $T_N$) and exhibits a more pronounced anomaly in the WFM region [21] as compared to $\alpha$-Fe$_2$O$_3$. In view of these observations, we investigated the temperature variation of lattice parameters for both $\alpha$-Fe$_2$O$_3$@CNT as well as the $\alpha$-Fe$_2$O$_3$ template. For the lattice parameters, the synchrotron XRD data of $\alpha$-Fe$_2$O$_3$@CNT sample have been fitted using two phase model in Rietveld profile refinement [32], corresponding to rhombohedral $\alpha$-Fe$_2$O$_3$ ($R$-3 $c$; hex-setting) and the CNT ($P$ 63 $m$ $c$) [39]. In case of the template, all the peaks are identified with $\alpha$-Fe$_2$O$_3$ (figure 1(h)).

For both the samples, lattice parameters corresponding to $\alpha$-Fe$_2$O$_3$ phase as well as the respective volume of its unit cell are compared in figures 5(a)–(c). Significant compression effects are observed in the entire temperature range (20–300 K) for both the ‘a’ and ‘c’ lattice parameters of $\alpha$-Fe$_2$O$_3$@CNT (blue dots) as compared to its bare nano particles (red dots). A slight anomaly in the lattice parameters of $\alpha$-Fe$_2$O$_3$ around $T_M$ is seen in both the samples. In this aspect, the data are similar to that observed in bare $\alpha$-Fe$_2$O$_3$ nano crystals formed using hydrothermal method [21, 49].

Surprisingly, we find a pronounced feature in the lattice parameter ‘a’ of the graphitic phase (corresponding to a CNT), which coincides with the Morin transition $T_M$, intrinsic to the oxide encapsulate (figure 5(d)). A slight anomaly at this temperature also exists for the lattice parameter ‘c’ corresponding to the CNT (figures 5(d)-(f)). The observation of anomaly in the graphitic phase at the magnetic transition of the oxide encapsulate provides promising evidence of the interface effects. This interface effect also appears to be related to the significant enhancement in the magnitude of the remanence, as we have experimentally observed (figure 4(a)) in $\alpha$-Fe$_2$O$_3$@CNT.

At this point it is interesting to recall that MnCO$_3$, is known to be a stronger WFM/PzM as compared to $\alpha$-Fe$_2$O$_3$ due to its lower Néel transition temperature [2, 10, 14]. As also mentioned before, larger $T_N$ implies stronger AFM super exchange, leading to smaller spin canting in $\alpha$-Fe$_2$O$_3$. Thus, both WFM and PzM effects are relatively smaller in bare $\alpha$-Fe$_2$O$_3$ ($T_N \sim 950$ K) as compared to MnCO$_3$ ($T_N \sim 30$ K) [2, 3, 10, 14]. Interestingly, the time-stable remanence also reflects this correlation. From the remanence data obtained on a number of canted AFM, not only hematite but also on a number of DMI driven carbonates including MnCO$_3$ [21]...
NiCO₃ and CoCO₃ (unpublished), we consistently find that the magnitude of time-stable remanence bears an inverse correlation with the Néel temperature. This feature is reflective of the extent of spin canting, through simple magnetization/remanence measurements in symmetry allowed cantent AFM [21, 49].

From present set of data it is evident that the magnitude of remanence observed in α-Fe₂O₃@CNT at 300 K (this work) is now at par with that observed in MnCO₃ below 30 K [21]. The anomaly in the lattice parameters near \( T_M \) in case of graphitic shells in α-Fe₂O₃@CNT (figure 5(e)) is also more pronounced than what is observed in the lattice parameters of pure MnCO₃ in its WFM phase [21]. Thus, we propose that encapsulation of α-Fe₂O₃ within a CNT leads to strain and interface effects, which, in turn, modulate the spin canting angle, Fe–O–Fe bond angle and bond lengths [2, 3]. The strain effects, as evident from volume compression (figure 5(c)), are likely to modulate the WFM phase as this can affect both the spin canting angle and a Fe–O–Fe bond lengths/bond angles associated with AFM super exchange [2, 3]. The enhancement in both the magnetization and the remanence is also consistent with these strain effects in the lattice parameters which are significantly large for α-Fe₂O₃@CNT. Especially with control experiment on the bare hematite, it appears that the observed enhancement in the magnitude of remanence is related to larger spin canting.

This also implies that the SOC associated with the spin canting phenomenon of the oxide encapsulate is transmitted...
to the graphitic shells, particularly to its in plane lattice parameter ‘a’. Though microscopic measurements [40–43] are certainly needed to confirm this, it appears that the huge enhancement in the magnitude of magnetization as well as remanence is arising due to this interface effect, which primarily exists between the lattice parameters of α-Fe₂O₃ and the CNT. It is also to be recalled that due to curved surface of a CNT, as compared to graphene, the SO coupling is considered to be larger [29]. There also have been recent reports on interfacial DMI on graphene/ferromagnetic metal based heterostructures [44]. However, encapsulation of a symmetry allowed DMI driven canted AFM inside a CNT, such as shown here, clearly augments the effect as is evident from figures 4 and 5.

3.6. Magnitude of time-stable remanence at room temperature

The highlight of the present work is the time-stable remanence, exclusively arising from the weak ferromagnetic phase [21, 45–47], which has been enhanced by an order of magnitude by encapsulation of α-Fe₂O₃ inside a CNT. Looking at time-stable remanence as the capacity of magnetization retention, two important aspects are its (i) magnitude, and (ii) holding time. Since room temperature is more relevant for practical applications, we tabulate the M and remanence data at 300 K for the sample α-Fe₂O₃@CNT (table 1). Up to 70% of in-field M is retained (in the form of remanence) after removal of H ∼ 100 Oe and 40% in case of H ∼ 1000 Oe for the sample α-Fe₂O₃@CNT. These H values can easily be achieved by bar magnets. After removal of H, the magnetization decays with time ∼0.5% in the measurement time span of two hours α-Fe₂O₃, whereas it is ∼5% in case of the template (table 1, figure 4). The remanence is stable and larger at 300 K than at 5 K, further confirming the magnetization dynamics in weak ferromagnetic region is different from other magnetic systems including spin glasses and other nano scale AFM [17–20]. This effect is observed at room temperature, and therefore it holds promising technological implications. For instance, in routine FM/AFM exchange bias [48] systems, replacing antiferromagnet with a WFM should provide a new and a very robust magnetization pinning. This pinning requires rather low magnetic fields and should also be tunable by stress.

4. Conclusions

In conclusion, the appearance of time-stable remanence is intimately related to Dzyaloshinskii–Moriya interaction driven spin canting phenomenon in WFM s such as hematite. Encapsulation of this oxide inside CNTs provides novel interface effects that lead to much significant enhancement in the magnitude of the time-stable remanence at room temperature. Thus, encapsulation inside CNTs appears to be the most efficient way to manipulate spin canting and the associated weak ferromagnetism. It is to be emphasized that the method of encapsulation of this multifunctional oxide inside the CNT is cost effective, scalable, and provides ease of integration for direct patterning into spintronic devices.

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Table 1. Numerical values of $M_{2PC}$ and remanence for α-Fe₂O₃@CNT at room temperature to depict the magnetization retention.

| Field (Oe) | T(K) | $M_{2PC}$ (emu g⁻¹) | Remanence (μ) (emu g⁻¹) | Magnetization retention (%) ($\mu$/M$^{2PC}$)100 |
|-----------|------|---------------------|-------------------------|-----------------------------------------------|
| 100       | 300  | 0.464 13            | 0.320 24                | 69%                                           |
| 1000      | 300  | 1.487 52            | 0.599 32                | 40%                                           |
| 10 000    | 300  | 2.5721              | 0.2344                  | 9%                                            |

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