



Bistable magnetic nanowires: A new approach to non-volatile memory with single readout and automatic deletion

Yenni G. Velázquez Galván¹, Armando Encinas^{2,a)}, Juan Manuel Martínez-Huerta³, Luc Piraux⁴, Joaquín de la Torre Medina^{5,a)} 

¹Departamento de Matemáticas y Física, Instituto Tecnológico y de Estudios Superiores de Occidente, Periférico Sur Manuel Gómez Morín 8585, 45604 Tlaquepaque, Jalisco, Mexico

²División de Materiales Avanzados, Instituto Potosino de Investigación Científica y Tecnológica A. C., Camino a la Presa 2055, 78216 San Luis Potosí, San Luis Potosí, Mexico

³Escuela de Ingeniería y Ciencias, Tecnológico de Monterrey, Atlxcáyotl 5718, Reserva Territorial Atlxcáyotl, 72453 Puebla, Puebla, Mexico

⁴Institute of Condensed Matter and Nanosciences, Université catholique de Louvain, Place Croix du Sud 1, B-1348 Louvain-la-Neuve, Walloon Brabant, Belgium

⁵Instituto de Investigaciones en Materiales-Unidad Morelia, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex Hacienda de San José de la Huerta, 58190 Morelia, Michoacán, Mexico

^{a)}Address all correspondence to these authors. e-mails: armando.encinas@gmail.com; delatorre@materiales.unam.mx

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A novel approach for a non-volatile destructive readout memory application using bistable magnetic nanowire arrays is presented. The encoded information is stored as binary 1 and 0 by groups of NWs magnetized in the positive and negative states, respectively. We leverage the naturally occurring switching field distribution of the NW array and a tailored alternating decreasing magnetic field to program remanent magnetic states. To retrieve the information, the measured remagnetization curve exhibits a star-like behavior with jumps and plateaus and its derivative converts this information to a binary-type format. Two encoding and readout schemes are proposed and validated: binary bits and barcodes. For each case, the implementation and optimization procedures are illustrated, along with the required processing to obtain a useful readout signal. This strategy holds potential for non-volatile memory applications in which the stored information is erased during reading and can be reused indefinitely.

Introduction

Evidence suggests that the unprecedented growth of the Internet of Things (IoT) devices worldwide has triggered an evolution in new technologies, focusing on memory [1]. The issue has grown in importance in light of recently expanded global ecosystems that use objects with internet connectivity through embedded electronics. This relates to smart machine communication using embedded sensors, controllers, and communication systems. It involves collecting and processing large amounts of data stored and shared in “The Cloud.” Therefore, there is an increasing concern to develop computational resources to manage all this information, and the modern generation for reliable and secure non-volatile memory (NVM) to perform code storage, sensor trimming, device configuration,

tag security for identity theft [2, 3], and other storage functions [4, 5].

The challenges to developing new nanoscale NVM devices are improving performances in terms of minimal dimensions and cost, fast and sizable transfer of data, retention, endurance, and high energy efficiency leading to lower power consumption [4, 6, 7]. NVM technologies can manipulate persistent data directly in memory [8]; however, data are persistent after the systems power-off, creating security vulnerabilities [9]. As a result, much research has been devoted to optimizing data security in NVM, allowing single readout and automatic deletion using data encryption [10–13]. To reduce this performance impact, recent developments in binary encoding systems have heightened the need to explore nanoscale-based materials [14–18] (Fig. 1).

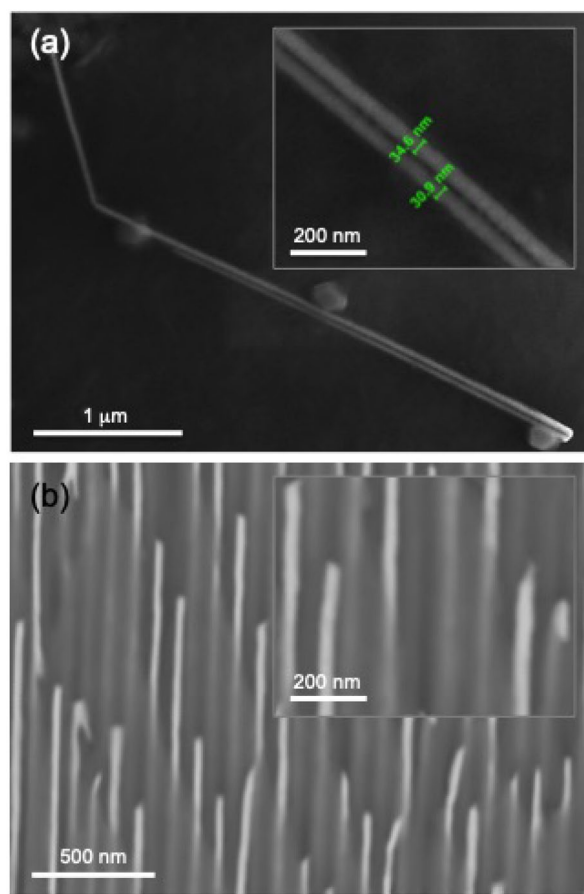


Figure 1: Scanning electron microscopy images (a) of Co NWs observed after the dissolution of the polycarbonate membrane and (b) of the cross-section of an alumina membrane containing CoFe NWs within the pores. The inset in each figure displays a close view of the NWs.

In particular, magnetic materials have been extensively studied and applied as analog as well as digital magnetic storage media due to their well-known non-volatile properties, large storage capacity, and low cost [19, 20]. In addition, magnetic storage is read-write which makes it possible to reuse the storage capacity over and over by deleting older data. Along these lines, electrodeposited high aspect-ratio magnetic nanowire (NW) arrays have attracted much attention due to their large-scale reproducibility and low-cost fabrication for which elaborate processes like electron lithography are not needed. This fabrication technique has also proven to be very versatile as it allows the fabrication of a vast variety of materials with control over their main geometrical parameters, which has led to its widespread use over the last decades [21–23]. Furthermore, these nanostructures display stable discrete binary states that can be used to store non-volatile and reconfigurable information, meaning that they support read-write procedures [19, 24–26]. These features of NWs were recognized and led to the proposal of the quantum magnetic disk in which individual bistable wires are used as single binary bits [27, 28], analogous to modern bit-patterned

media, a technology still in development. Another approach considers writing information as barcodes using bistable NWs, which works much like the magnetic strip in cards, with spatially distributed barcoded regions [29]. Despite these efforts, there is an important opportunity and interest for novel non-volatile storage approaches that can take advantage of the stable discrete binary nature of magnetization in NW arrays.

Herein, we propose a different approach to apply bistable magnetic nanowires to develop non-volatile destructive readout memories. Instead of using individual NWs as digital binary bits, as it is done with bit-patterned media, we use the naturally occurring switching field distribution (SFD) to encode (write) information using binary (1 and 0) groups of NWs. These groups correspond to specific subsets of the SFD defined by a switching field interval. The general idea is that information can be stored as a programmed remanent state formed by a user-defined set of binary groups of NWs magnetized in the positive (1) or negative (0) states, using an alternating decreasing magnetic field (ADMF) procedure. These remanent states possess long-term stability [19], thus the non-volatile property. The information is read, and erased at the same time, from the remagnetization curve (RMC) obtained by applying a positive increasing magnetic field from zero to saturation [24]. Since the initial (remanent) state only contains groups of NWs ordered in increasing switching field order, the RMC shows a stair-like behavior with a sequence of jumps and plateaus, whose respective height and width depend on the tailored field intervals used in the ADMF process.

Indeed, the jumps in the RMC correspond to the switching of those NWs initially magnetized in the negative state while the plateaus correspond to the NWs already magnetized in the positive state and who do not switch. By taking the derivative with respect to the applied field of the RMC, we obtain the differential susceptibility in which the stair-like feature yields a curve resembling a square digital signal [30]. In turn, this signal can be exploited for binary bits and barcodes as novel non-volatile encoding and destructive readout memory applications.

Results and discussion

Configurable remanent states by alternating decreasing magnetic field cycling

2D Arrays of bistable low-diameter NWs with a large height-to-diameter aspect ratio are simple and well suited to serve as binary non-volatile memory elements [19]. These NWs are only magnetized in the positive or negative directions along their easy axis which is the long axis of the wire. The entire array kept in, or contained by, the template behaves as a model 2D, exchange decoupled, identical particle Preisach-type system [19, 24, 31]. Non-saturated states consist in NWs magnetized in the positive and negative magnetization directions forming intricate

labyrinth-type patterns distributed spatially over the entire array [32–35]. The switching behavior of the NW array is described by the SFD, which is specific to each system. The SFD describes the dispersion of the individual switching fields. It is ubiquitous in particle assemblies and arises from variations in the microstructure between constituent elements and the dispersion in their geometrical parameters.

The aforementioned characteristics are ideal for the use of these NW arrays to encode information in the form of tailored, user-defined, stable remanent states from which the information can be retrieved and erased during the reading process. Moreover, leveraging the naturally occurring SFD, no spatial patterning is required since the information is retained in magnetic states defined not by their position, but by specific switching field intervals.

In order to obtain these tailored remanent states, the system is subjected to an ADMF sequence between positive and negative reverse fields obeying the rule $|H_i| > |H_{i+1}|$ for $i = 0, 1, 2, \dots, n - 1$, where n is the total number of reverse fields. In this notation, $H_0 = H_s$ corresponds to the saturation field that serves as the starting point for the ADMF encoding sequence. The sequence is completed once the last field in the sequence (H_{n-1}) is reached and then taken to zero leading to the stable unsaturated remanent state. This procedure is shown as a dotted line in Fig. 2(a) for the S1 Co sample, along with the hysteresis loop. The corresponding RMC, dashed line, is recorded from the remanent state up to the saturated state by applying an increasing magnetic field from zero up to a saturation field. The jumps and plateaus observed in the stair-shaped RMC correspond to groups of NWs that switch their magnetization back to the direction of the applied field and to groups of NWs whose magnetization remains parallel to the field, respectively, as pointed out in a previous work [24].

Figure 2(b) compares the SFD (dash-dotted line) along with the RMC (dashed line) and its derivative, $\chi = dM_0/dH$ (continuous line). The field extrema of the ADMF used to obtain the corresponding RMC curve are shown for reference as vertical dotted lines. As seen in the figure, the derivative of the RMC is contained by the SFD, and the stair-like behavior is seen in the derivative as jumps between high and low values. These jumps take place at the field values H_i used in the ADMF sequence [24, 30]. Therefore, the specific shape of the RMC curve and its derivative depends on the SFD of the magnetic material and the specific ADMF sequence used to reach the non-saturated remanent state. This means that it is possible to program different RMCs for the same material using different ADMF sequences.

We propose using the $\chi = dM_0/dH$ curves as information that was encoded by writing using ADMF sequences that is read by applying a readout field. This corresponds to a non-volatile destructive readout memory in which information is stored in a non-volatile fashion and erased or destroyed by the reading

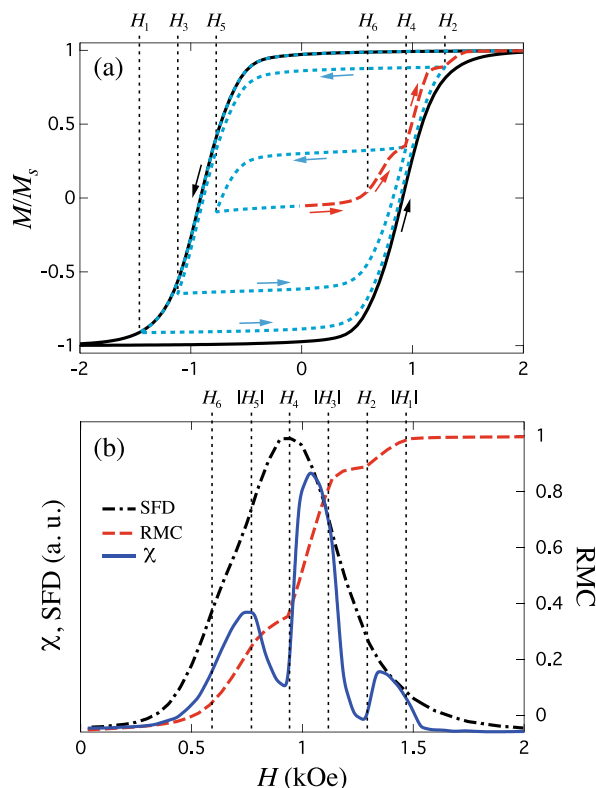


Figure 2: (a) Major hysteresis loop (continuous line), the demagnetization curve (dotted lines) obtained by the ADMF sequence defined by the fields $H_1, H_2, \dots, H_5$ and the corresponding RMC (dashed line) recorded by magnetizing the sample from remanence to positive saturation (Sample S1). (b) Comparison between the SFD (dash-dotted line), the RMC (dashed line), and the susceptibility curve (continuous line). For reference, the vertical dashed lines indicate the field extrema of the ADMF used to configure the corresponding unsaturated remanent state.

procedure. Moreover, this type of memory material can be used indefinitely to write and read information over and over again.

In the following, we consider two approaches to exploit the SFD and the ADMF sequences to encode information using groups of NWs magnetized in the positive and negative directions. The first one divides the usable portion of the SFD in equal field intervals or bins. Then the information is stored and read as 1 (high) and 0 (low) values in each bin, and information is encoded as binary numbers. The second approach divides the usable portion of the SFD in an arbitrary number of intervals of arbitrary length, so that the information is encoded as a barcode. In the next sections, we show the implementation of these approaches.

Application to encode and read binary numbers

As pointed out above, one approach is to use the ADMF encoding of tailored remanent states to store information as binary numbers. To this end, the usable portion of the SFD is divided into equal field intervals (or bins). The number of bins

corresponds to the byte size and each bin is a bit. The individual bits store information as 1 (high) or 0 (low). For example, in Fig. 2(b), we can see that the field sequence of the ADMF is such that it divides the central part of the SFD in equal intervals while excluding the tails of the distribution. So for each SFD, the usable portion, or field interval, must be defined. Then, the byte size or number of bits has to be established considering that the values of $\chi = dM_0/dH$ depend on their position within the SFD and on the width of the field interval of the individual bits.

Indeed, as seen from Fig. 2(b); the peaks in χ do not have the same amplitude because the RMC follows the SFD. The question arises as to how large the amplitude of a peak must be in order to be considered as a bit 1. To solve this issue first notice that χ always lies beneath the SFD which is due to the fact that the RMC is contained within the major hysteresis loop. That is, χ is lower than the SFD because in the numerical differentiation, the magnetization increments ΔM of the RMC are lower than those of the ascending part of the major hysteresis loop for the same field increments ΔH . Furthermore, since the RMC and χ correspond to the switching of a subset of the total assembly (NW array), the SFD acts as an envelope of χ . This feature can be exploited to normalize χ with respect to the SFD and then to compare the relative amplitude between different peaks and to discern which ones can be considered as bit numbers 1.

Figure 3 shows the comparison between the normalized susceptibility curves by the SFD, $\chi_N = \chi/(dM/dH)$, and the corresponding RMC obtained using different encoding ADMF sequences, for Co NW arrays S1 and S2. As seen, χ_N differs from the ideal square waveform in which bits 1 and 0 are easily assigned. In this case, the normalized susceptibility ranges

around 0.5 without reaching the extreme values 1 and 0. So to determine whether the decoded information corresponds to a bit 1 (or bit 0) the criterion $\chi_N \geq 0.5$ (or $\chi_N < 0.5$) at the middle of each interval within the vertical dotted lines is used. The red circles in Fig. 3(a) show the points over χ_N that fulfill this criterion.

The binary numbers 0101010 and 1010101 obtained using sample S1 are displayed in Fig. 3(a) and (b) within the shaded area in the predefined field interval 0.68 to 1.73 kOe. Observe that these binary numbers are configured using similar ADMF sequences of the form $+H_0 \rightarrow -H_1 \rightarrow +H_2 \rightarrow \dots \rightarrow -H_7$ with $\Delta H = 0.15$ kOe. These ADMF sequences are shown on top of both Fig. 3(a) and (b) and the difference between them is the choice of the first reverse field H_1 value, which is equal to 1.73 kOe for number 0101010 and 1.58 kOe for number 1010101.

Moreover, the role of the coercive field is reflected on the width of the field interval in which bit numbers can be configured upon an ADMF. The larger the coercive field of a NW array, the larger and wider its corresponding SFD. In this work, three Co NW samples S_i ($i = 1, 2, 3$) have been designed with different coercive field values H_{ci} , such that $H_{c1} < H_{c2} < H_{c3}$.

Indeed, sample S2 has a larger coercive field and a wider SFD in comparison with that for sample S1, which allows configuring bit numbers in a larger predefined field interval that spans from 1 to 5.35 kOe. As seen in Fig. 3(c) and (d), the same binary numbers of Fig. 3(a) and (b) can be configured in a wider interval with a larger field decrement $\Delta H = 0.66$ kOe. In this case, the different initial reverse fields of $|H_1| = 4.73$ kOe and $|H_1| = 5.35$ kOe have been used to configure the binary numbers 0101010 and 1010101, respectively.

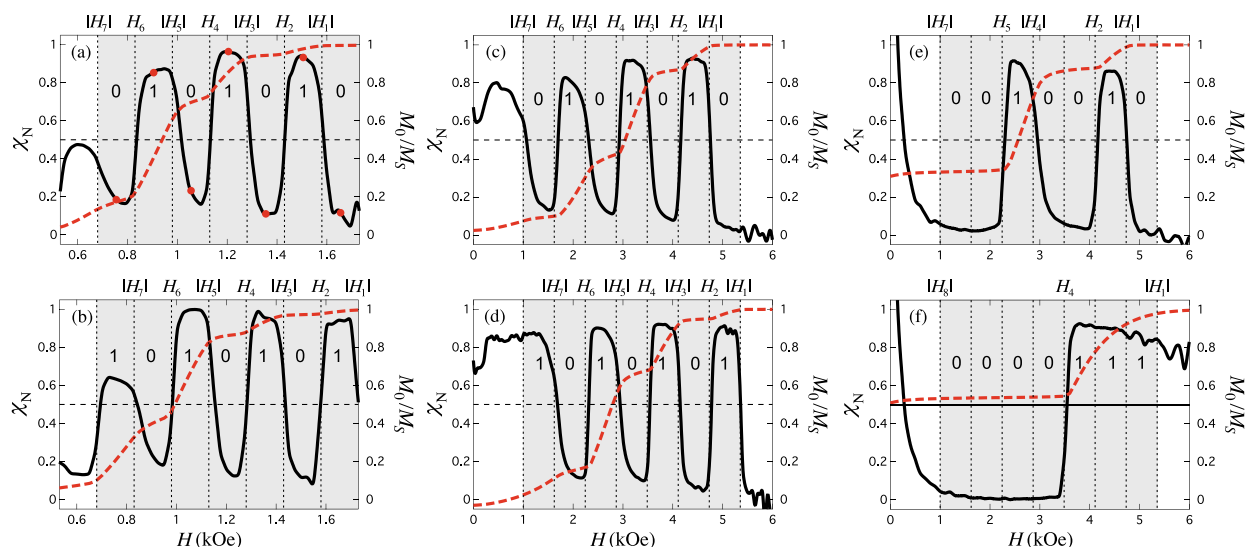


Figure 3: Normalized susceptibility curves χ_N (continuous lines) obtained from the RMC (dashed lines) configured with different ADMF sequences for the NW array samples (a, b) S1 and (c-f) S2. The reverse fields used in sequence are indicated on top of each graph and the binary digits within the shaded zones are defined as 1 or 0 whether $\chi_N \geq 0.5$ or $\chi_N < 0.5$ (see the horizontal dashed line) at the middle of each interval within the vertical dotted lines. The red circles in (a) are guides for the eye for these points.

Binary numbers containing two or more successive binary digits 0 or 1 are encoded by concatenating their respective field intervals. This is, using a larger field interval which is simply a multiple of the original field interval ΔH . For instance, in order to configure n equal consecutive binary digits 0, the field swept or sub-sequence $+H_{i-n} \rightarrow -H_i \rightarrow +H_{i+1}$ has to be included in the complete encoding ADMF sequence. In this sub-sequence, a field decrement of $n\Delta H$ is used between the reverse fields $+H_{i-n}$ and $-H_i$. Next, the n consecutive binary digits 0 are decoded by switching first the magnetization of the NWs group g_i in the field sweep $H_{i+1} \rightarrow |H_i|$. At this point, the NWs groups g_{i-1} to g_{i-n} are in a stable magnetic state and already have positive magnetization; thus, no switching of the magnetization takes place in the field sweep $|H_i| \rightarrow H_{i-n}$.

An example of this procedure is the binary number 0010010 shown in Fig. 3(e), which is encoded using the ADMF sequence $-H_1 \rightarrow +H_2 \rightarrow -H_4 \rightarrow +H_5 \rightarrow -H_7$. In the remagnetization process, there is no magnetization reversal in the field sweep $|H_7| \rightarrow H_5$ where two consecutive bits 0 are decoded because the array of NWs is in a stable magnetic state. This is contrary to what is observed in the field sweep $H_5 \rightarrow |H_4|$ where group g_4 switches its magnetization back to the positive state. At this point, groups g_3 and g_2 already have positive magnetization and the array of NWs is in a stable magnetic state in the field sweep $|H_4| \rightarrow H_{4-n}$ in which $n = 2$. As a result, another two consecutive binary digits 0 are decoded. Finally, group g_1 reverses its magnetization to the positive state in the field sweep $H_2 \rightarrow |H_1|$. At this new point, the array of NWs is in the saturated state and then in a stable state, which is responsible for the last binary digit 0 in the predefined field interval within the shaded area.

Furthermore, a similar ADMF sequence to the one discussed above must be used if consecutive bits 1 are to be encoded. To encode n consecutive bits 1 after m bits 0, a sub-sequence like $-H_{i-n} \rightarrow +H_i \rightarrow -H_{i+m}$ must now be included in the complete sequence. Consider for instance the binary number 0000111 shown in Fig. 3(f), which is encoded with the sequence $-H_1 \rightarrow +H_4 \rightarrow -H_8$. Using this simple sequence allows encoding three consecutive bits 1 after four consecutive bits 0 by considering H_4 as the reference reverse field H_i with $n = 3$ and $m = 4$. In this case, the field sweep $|H_8| \rightarrow H_4$ allows decoding four bits 0, provided that the magnetic state is stable, otherwise, m must be adjusted to encode/decode the appropriate amount of bits 0. Since no other stable states have been encoded within the interval from H_4 to $|H_1|$, the RMC increases monotonically without displaying steps and three consecutive bits 1 are thus decoded.

Application to encode and read barcodes

Barcode is a widely used method that consists of encoding information in a series of printed bars of different widths and

spacings between them. In this section, we propose a barcode encoding and decoding procedure based on ADMF sequences that define the widths of the bars and the blank spaces between them. For instance, an encoded barcode (EBC) for sample S4, shown as shaded gray areas in Fig. 4(a), is defined by the reverse fields used in the ADMF sequence displayed on top of this figure. As seen, gray bars are set only in the field ranges between reverse fields H_{i+1} and H_i with $i + 1$ and i being pair and odd subscripts, respectively.

As in the binary numbers application of the previous section, the decoding process is also performed by using the susceptibility curve χ , that is the RMC derivative. Then, bars in a decoded barcode (DBC) are obtained from the different peaks in χ which result from the magnetization switching of NWs groups with magnetization oriented antiparallel to the applied magnetic field during the remagnetization process. It must be stressed that, contrary to the binary numbers application, the reverse fields H_i used in the

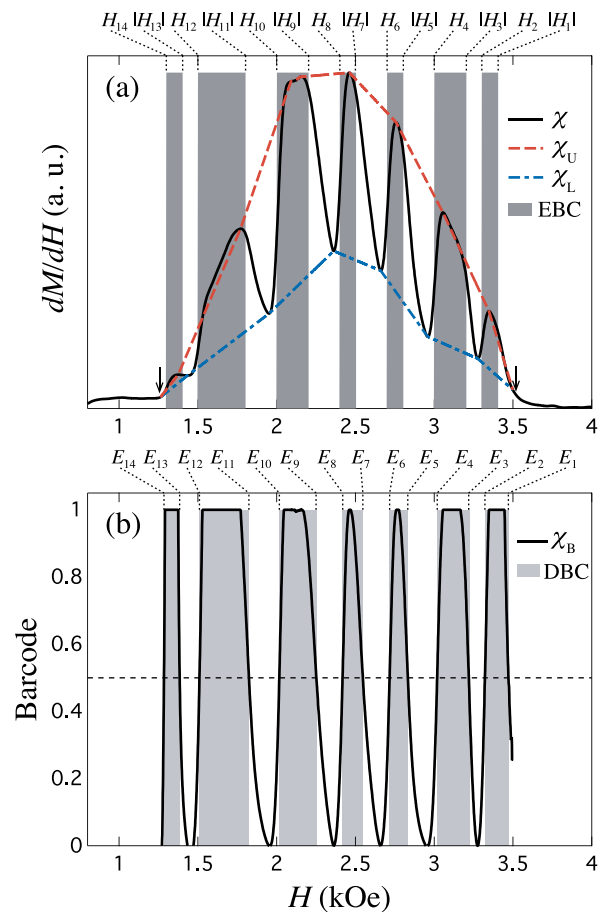


Figure 4: (a) Comparison between the susceptibility curve χ (continuous line), the interpolated upper χ_U (dashed line) and lower χ_L (dotted line) envelope susceptibility curves and the EBC (shaded bars) for sample S4. (b) The transformed susceptibility curve χ_B (continuous line) obtained using Eq. (1) is compared with the DBC (shaded bars). The ADMF and extreme field sequences used for the EBC and DBC are indicated on top of figures (a) and (b).

ADMF sequence are numbered in a consecutive way and the field decrement ΔH can be different between consecutive H_i values. Then, for this application, a predefined magnetic field interval is not necessary since the DBC procedure is rather based only on considering significant changes in χ . The central idea of this application is to obtain the same width and spacing for both the encoded and decoded bars.

To determine the DBC it is necessary to define the width and position of each bar by performing a mathematical transformation to χ . This transformation consists in defining first an envelope for χ in terms of the upper (χ_U) and lower (χ_L) envelope susceptibility curves which connect separately the local maxima and minima between them with interpolated straight lines, as seen in Fig. 4(a). To this end, the extreme field values of the whole interval where significant changes in χ are observed are identified by the vertical arrows at the bottom of the curve in Fig. 4(a). Using χ_U and χ_L allows defining the barcode susceptibility function as

$$\chi_B = \frac{\chi - \chi_L}{|\chi - \chi_U| + \chi_U - \chi_L}. \quad (1)$$

This transformation stretches χ in such a way that points very close to the curve local maxima and minima are shifted very close to 1 and 0, respectively. As in the case of the EBC, bars in the DBC can be defined as the zones between extreme fields E_{i+1} and E_i of the field intervals beneath the full width at half maximum (FWHM) of the distinct peaks in χ_B [horizontal dotted line in Fig. 4(b)], with $i + 1$ and i being pair and odd subscripts. The comparison between Fig. 4(a) and (b) shows a good agreement

between the position and widths of the bars for both the EBC and DBC.

Figure 5 shows a comparison between EBCs and DBCs obtained using different reverse field sequences for Sample S4. As seen, a fairly good agreement between the EBCs and DBCs is found for all encoding ADMF sequences. Clearly, the width of the bars directly depends on the number of reverse fields and a better agreement between the EBCs and DBCs is observed when a larger number of bars are encoded, as shown in Fig. 5(b) and (d). Contrary to what is observed for the binary numbers application, for sample S1 with a lower coercive field value (see Fig. 3(a) and (b)), in this case, wider barcodes with a larger number of bars can be encoded because of the larger field interval where magnetization switching takes place as a consequence of the corresponding larger FWHM of the SFD. This reveals that a larger fragmentation of this field interval with a larger number of NW groups with alternate magnetization leads to more accurate DBCs. Besides, a general feature of all the DBCs shown in Fig. 5 is a slight field shift and a larger width in comparison with that for the EBCs. This small discrepancy can be ascribed to the limited accuracy of the proposed methodology based on Eq. (1) to determine the width of the bars at the extreme sides of the DBCs. Indeed, a larger error in the bars width and position is expected at the extreme sides of the barcodes because they result from smaller peaks than those at the center of χ .

A standard and frequently used ADMF sequence that leads to peaks with very low amplitude is the AC demagnetization process. In this procedure, the difference between consecutive

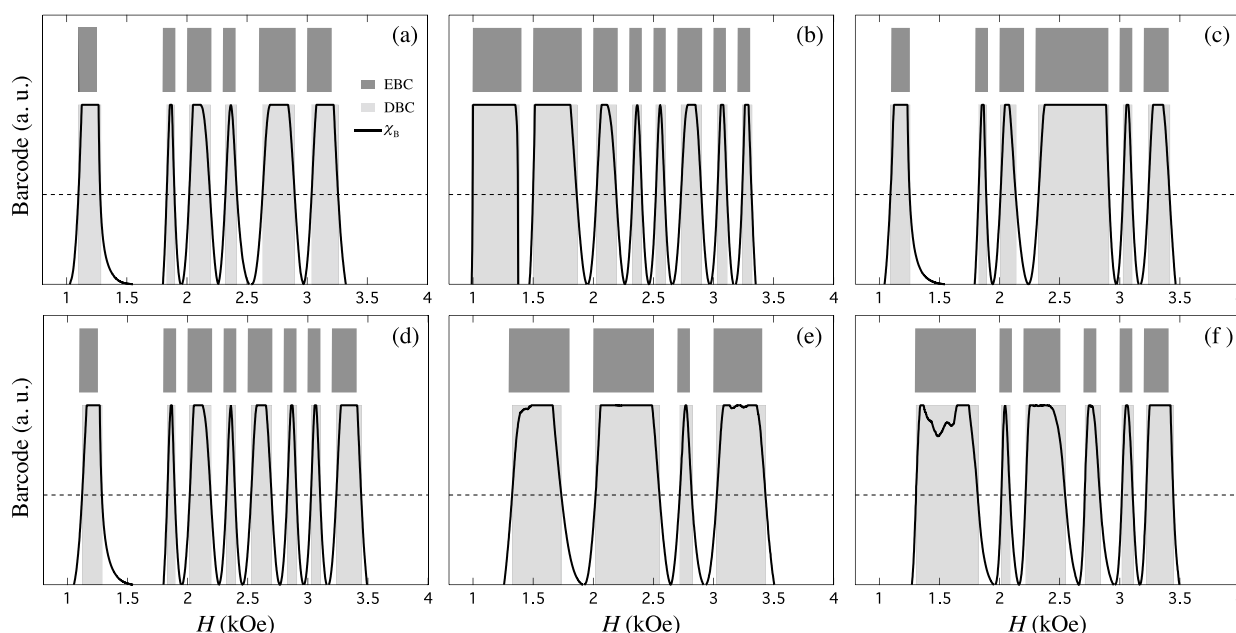


Figure 5: Comparison between EBCs (dark gray bars) and DBCs (light gray bars) obtained from different encoding ADMF sequences and RMCs using sample S4. The transformed susceptibility curve χ_B is added to each graph as a comparison and the horizontal dotted line indicates the FWHM that defines the width of each bar in the DBCs.

reverse field values is $\Delta H_i = \alpha H_i$ with $\alpha < 1$ as the AC demagnetization percentage parameter of the reverse field H_i . This parameter leads to $H_{i+1} = (\alpha - 1)H_i$, which in turn implies that any field H_i in the sequence can be obtained from the initial saturation field (H_0) as

$$H_i = H_0(\alpha - 1)^i. \quad (2)$$

Figure 6 shows the DBCs (light gray bars) calculated using Eq. (2) from AC demagnetization sequences configured with α values of 0.10, 0.07, 0.05, and 0.02 for sample S3. As seen from the comparison between the DBCs and EBCs (dark bars), there is a better agreement for bars at the center of χ for $\alpha \geq 0.05$. As expected, in all cases, a field shift between EBCs and DBCs is evident for bars resulting from smaller peaks at the extreme sides of χ , which is consistent with what is observed for the barcodes in Fig. 5. Besides, the accuracy of the proposed method to obtain the DBCs depends on the lineshape of χ and particularly on the peaks amplitude and the ability to find the corresponding maxima and minima in the χ curve (see Fig. 4). The appearance of peaks on χ is possible only if well-defined jumps between plateaus in the RMC can be induced, which is not possible if

the field decrement $\Delta H_i = |H_i| - |H_{i+1}| = \alpha |H_i|$ between adjacent return fields is very low or comparable to the measurement resolution. Indeed, as seen in Fig. 6(d) using $\alpha = 0.02$ and $H_0 = 7$ kOe leads to the disappearance of peaks on χ below $H_{62} \approx 2$ kOe for which $\Delta H_i \leq 40$ Oe for $i \geq 62$. The disappearance of peaks on χ below this ΔH_i value is due to the chosen field increment of 50 Oe for the magnetization measurements in this study. This feature explains the disappearance of peaks on χ for $\alpha = 0.05$ below $H_{34} \approx 1.22$ kOe for which $\Delta H_{34} \approx 61$ Oe, again quite close to the measurement resolution of 50 Oe. As a consequence, the absence of peaks on χ with well-defined maximum and minimum directly leads to incomplete DBCs, as observed in Fig. 6(c) and (d).

These results show that the accuracy of the proposed encoding/decoding procedure strongly depends on the resolution used for the magnetization curve measurements, such that a better matching between the EBCs and DBCs can be obtained using magnetization measurements with increased resolution. Therefore, arrays of bistable low-diameter NWs are convenient systems with encoding and decoding-destructive readout capabilities. This means that after the decoding

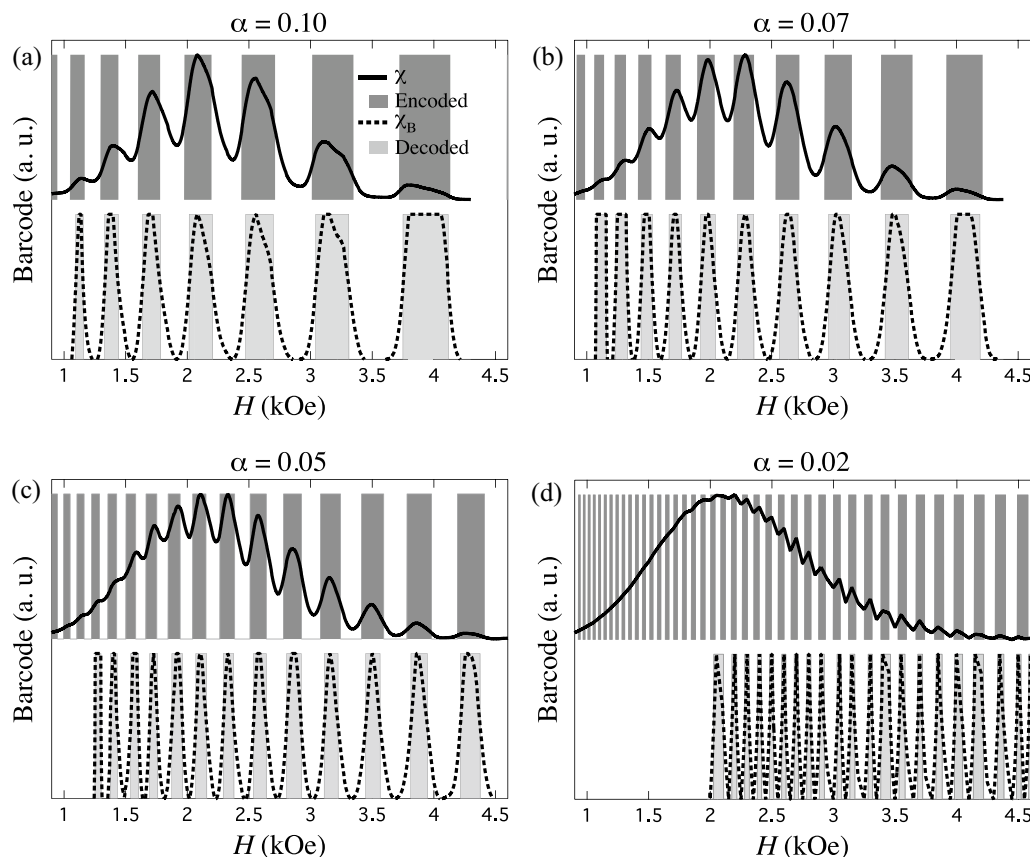


Figure 6: Comparison between EBCs (dark bars) and DBCs (light gray bars) obtained from RMCs configured using different AC demagnetization sequences with sample S3. The corresponding susceptibility (χ) and transformed susceptibility (χ_B) curves are shown for comparison. The reverse fields for each AC demagnetization sequence were obtained using Eq. (2) with α values of (a) 0.10, (b) 0.07, (c) 0.05, and (d) 0.02.

process, the system can be used for preparing a new EBC that can be stored for a long period of time by virtue of the NWs unsaturated states stability. Finally, it is important to underline three important features of the proposed non-volatile destructive readout memory based on NW arrays. First, it exploits the naturally occurring SFD inherent to magnetic particle assemblies, thus not requiring costly lithographic fabrication techniques. Secondly, the working principle was validated for NWs grown on polycarbonate as well as anodized alumina templates, making these compatible with both flexible and conventional electronics. Thirdly, the encoding and readout procedures require well-established technologies used to store and read information from magnetic media, making this approach suitable for large-scale applications.

The results show that information can be stored and read destructively, and erases up on reading, using bistable magnetic NWs and non-saturated magnetic states. Two storage schemes have been proposed and validated: in the first one, information is stored as binary numbers, and in the second one, as bar codes. Both approaches allow changing the number of “ones” (gray) and “zeros” (non-gray); however, as discussed above, there is a limitation when using small field intervals as it leads to smaller changes in the susceptibility. The smallest usable field interval is ultimately limited by the FWHM of the SFD, which is material-dependent. The writing mechanisms are not complicated; it results much simpler for the bar codes than for the binary numbers. However, depending on the application, binary encoding might be more advantageous than barcoded.

The readout signal obtained as the differential susceptibility of the initial magnetization curve requires to be processed to yield a useful digital signal, which, as we have shown, becomes limited as the field interval used for a given data becomes smaller. Regarding the usefulness of these types of destructive readout memories, it is important to mention that for both recording schemes, there are no movable parts and no processing is required for patterning. The information is encoded into the system without the need to use complicated fabrication procedures, in contrast to typical spatially distributed barcoded schemes such as those of magnetic stripes in cards or as the NW-based approach of Cisternas, et. al., that require movable parts [29]. Another advantage is that the center and FWHM of the SFD, and therefore the writing and reading fields, can be selected by changing the type of material or the characteristics of the template (wire density and diameter) or even by modifying their microstructure [36]. Overall, the present approach is an interesting alternative for non-volatile destructive readout memory applications which can be used as tickets, security tokens, and magnetic keys among others.

Conclusion

The bistable nature of arrays of low-diameter NWs has been shown to be a key requirement to create remanent states formed by groups of positively and negatively magnetized NWs. Based on this property, it is possible to configure endless stable states through different ADMF sequences. The NW groups can be sorted according to the distribution of coercive fields and separated via this process. The RMC obtained after the encoding process shows a discrete number of steps and jumps. The results show that the number of steps and their length depend solely on the reverse fields used in the ADMF sequence. Therefore, the use of these properties allows the design of a procedure for writing and reading information either as binary numbers or as barcodes. For the binary numbers application, ADMF sequences containing up to 7 bits have been encoded. The encoding protocol has been validated by decoding the stored information using the derivative of the RMC, namely the susceptibility curve χ , which displays maxima and minima that are associated with bits 1 and 0, respectively. In addition, another application of the encoding/decoding procedure consists of using the susceptibility curve to make barcodes. Contrary to the binary numbers application, barcodes take advantage of the position and separation between bars. In order to construct barcodes with good accuracy, a model has been developed which consists of a transformation of χ in order to decode the approximate ADMF sequence used in the encoding process. Our results show a simple approach to store and read information magnetically, which is a single-read application since the encoded information is erased during the readout. Therefore, a single NW array can be used to encode/decode repeatedly for a large number of times since the preceding stored information is erased during the decoding process. These findings have many important implications for destructive readout memory applications.

Materials and methods

Co and CoFe NWs were grown by electrodeposition using commercial nanoporous polycarbonate and anodized alumina membranes. These NW materials have been used since they have wide switching field distributions [36] which are helpful for the present study. The track-etched polycarbonate membrane (from it4ip S.A.) is 21 μm thick, with a pore diameter of 35 ± 5 nm parallel to each other but randomly distributed and an average porosity of 3%. The anodized alumina membrane (from Synkera Technology Inc.) has a 100 μm thickness and a porosity of 12%. The pores have a 35 ± 5 diameter, and they are parallel to each other and hexagonally ordered. Fig. 1(a) and (b)

shows scanning electron microscopy (SEM) images of a bunch of few Co NWs after dissolution of the polycarbonate membrane and the cross-section of an alumina membrane with CoFe NWs attached to the nanopore walls, respectively. The inset in each figure displays a close view of the NWs, showing their low rugosity and low diameter within the range of 35 ± 5 nm.

Nanowire arrays were grown at room temperature by three-probe electrodeposition using a Pt counter electrode and a constant reduction potential of $E = -0.95$ V vs an Ag/AgCl reference electrode. Before electrodeposition, conducting layers were evaporated on one side of the membranes to serve as cathodes, specifically Cr(10 nm)/Au(150 nm) [polycarbonate] and a Cr(10 nm)/Au(150 nm)/Cu(2 μ m)/Au(100 nm) [anodized alumina]. A CoFe NW array was grown in an anodized alumina membrane using a 30 g/l H_3BO_3 + 80 g/l $CoSO_4 \cdot 7 H_2O$ + 40 g/l $FeSO_4 \cdot 7 H_2O$ electrolyte. Three Co NW array samples were grown in polycarbonate membranes using electrolytes containing 30 g/l H_3BO_3 + 238.5 g/l $CoSO_4 \cdot 7 H_2O$, with pH values of 2.0, 5.2, and 6.6 in order to have NW arrays with different SFD widths [37, 38].

Magnetic characterization was done at room temperature using an alternating gradient magnetometer (AGM-Lake-shore) with a maximum external field of ± 10 kOe (CGS units) applied parallel to the NWs axis. Measurements included the major hysteresis loops, ADMF sequences, and remagnetization curves. The SFD is obtained as the derivative, dm/dH , of the ascending part of the mayor hysteresis loop, from where its FWHM has been determined.

A total of four NW array samples were prepared in this study, labeled hereafter as S1, S2, S3, and S4, corresponding to Co with coercive field $H_c = 0.9$ kOe and FWHM = 0.59 kOe. Co with $H_c = 2.9$ kOe and FWHM = 1.95 kOe, Co with $H_c = 2.1$ kOe and FWHM = 1.68 kOe, and CoFe with $H_c = 2.09$ kOe and FWHM = 1.93 kOe.

For the present study, the methodology that was followed begins with an analysis that shows how the non-saturated states are formed and how they can be programmed by an appropriate alternating decreasing magnetic field (ADMF). First, their application for encoding and retrieving information as binary numbers is analyzed. Then, their use for information storage and retrieval as barcodes is shown. Beginning, for each case, with the working principle and validation and followed by an analysis of the advantages and limitations of the method.

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Author contributions

YGVG: methodology, investigation, validation, and data curation. AE: conceptualization, funding acquisition, investigation, supervision, and project administration. JMMH: validation, methodology, and visualization. LP: supervision, writing-review and editing, funding acquisition, and resources. JTM: conceptualization, data curation, investigation, formal analysis, writing-original draft, writing-review, and editing.

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Data availability

The data that support the findings of this study are available upon the request from the authors.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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