

Two-Dimensional Programmable Manipulation of Magnetic Nanoparticles on-Chip

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Remote and precise manipulation of magnetic particles is required to meet the demands for high-throughput and location-specific analysis in lab-on-chip applications. In the last decade many techniques have been developed for the remote manipulation of fluid-borne magnetic particles for accomplishing different tasks in biology, medicine and chemistry. Magnetic tweezers^[1] are commonly employed for the handling of individual magnetic micro- and nano-particles with nano-scale accuracy over a limited spatial area. Micro fabricated current wires^[2] and micro-magnets^[3,4] allow simple transport of magnetic particles as well as complex operations such as continuous sorting^[5,6] and enhanced mixing,^[7] however, with a loss in the spatial accuracy. Although the individual strategies mentioned above have been developed to separately address one or more of the required tasks, techniques that permit an encompassing approach have yet to be achieved.

Successful attempts in this direction were recently reported using discrete patterned magnetic thin films micro-structures tailored to form transport lines that enable the programmable motion of single micrometer-sized magnetic particles by the application of time-variable external magnetic fields.^[8,9] Alternatively, thin film-based devices have been developed to trap and transport magnetic micro-particles via strong localized fields and gradients found at domain walls in garnet films.^[10–12] More recently, magnetically controllable artificial and biological micro-robots, the so called magnetotactic artificial robots,^[13] have been explored for micro-scale applications such as drug delivery and micro-assembly. However, none of these approaches combines capture, translocation along multiple trajectories, and release of individual magnetic particles of size not only in the micrometer range but also far below the micron, and with a control of the manipulation of the individual entity at both the micro- and nano-scale. In recent studies, it was

demonstrated that spatially constrained magnetic domain walls (CDWs) propagating in ferromagnetic nano-strips (nano-conduits) predefined over a chip, can magnetostatically couple to fluid-borne magnetic nano-particles.^[14–18] This property, together with the possibility of manipulating CDWs with nanometer scale accuracy in specifically designed magnetic conduits, have been combined in technology platforms, which encompass remote manipulation of individual as well as large population of magnetic particles, transportation over large distances, and fine manipulation with nano-scale resolution. However, till date, the manipulation capabilities of this class of devices were limited to *predefined* patterned paths, albeit, more than one path could be selected.^[16] For instance, in drug discovery the efficacy of chemotherapeutic drugs is often hampered by a limited understanding of their mechanism of action. Achieving a 2-dimensional (2D) accurate manipulation over large areas with a control at the single molecule level is crucial (for example, in order to monitor the interaction dynamics with single cells^[19]), and will open the way to single molecule biophysics in on-chip devices for drug discovery. Furthermore, such manipulation and positioning capabilities could also be used in photonic applications since they would allow assembling nano-particles in ordered structures on a surface by remotely controlling the distance and symmetry of the assembly, thereby enabling the formation of 2D lattices with adjustable photonic band gaps (so called colloidal photonic crystals^[20]).

In this communication, a novel device concept is presented that vastly extends the functionalities of CDWs based single particle conveyors defined on a chip surface by allowing for the capture, manipulation, and release of individual or multiple fluid-borne magnetic nano-particles, without any *priori* fixed pathway. The herein proposed technology is easy to reproduce on different functional substrates^[21] and can be used for a variety of applications in biology, chemistry, medicine as well as photonics, where a precise magnetic particle positioning is required.

The central aspect to this approach includes an array of magnetic nano- or micro-ring structures patterned on a chip surface. A magnetic ring sustains the continuous and precise displacement of CDWs as well as of magnetic nano-particles that couples magneto-statically to the displacing CDWs.^[22,23] As shown in **Figure 1(a)**, two CDWs can be easily created and positioned at predefined positions on the perimeter of the circular ring shaped magnetic conduit by applying a momentary external magnetic field H_s , intense enough to saturate the ring along the desired in-plane direction. Each CDW separates two regions of oppositely aligned magnetizations. Each magnetic region, a magnetic domain, has a head (a positive or north pole) and a tail (a negative or south pole). The resulting CDWs are therefore classified as head-to-head (HH) or tail-to-tail (TT). The

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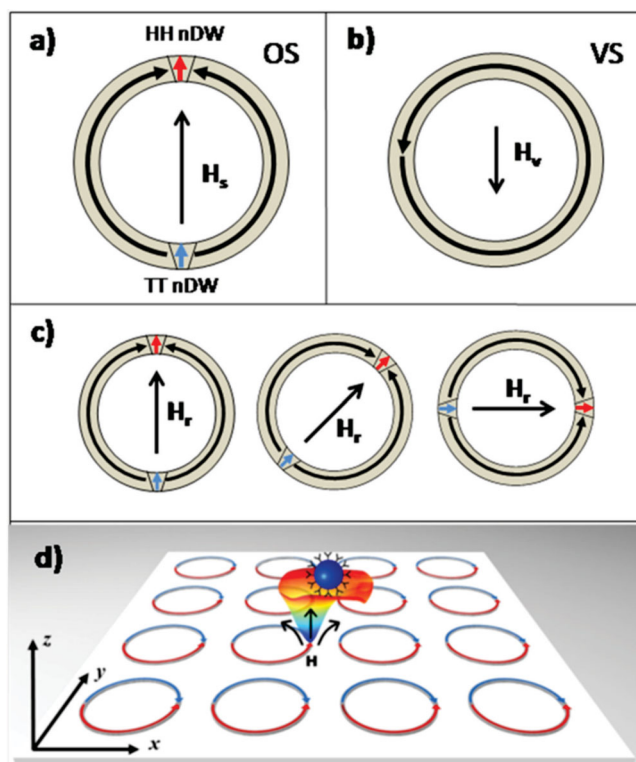


Figure 1. (a) Nucleation of onion-like-state (OS) with two constrained domain walls- head to head (HH CDW) and tail to tail (TT CDW), in a ferromagnetic circular ring by applying an external magnetic field H_s ; (b) Flux closure vortex state (VS) induced from OS by a reversal field H_v ; (c) Synchronous rotation of the HH and TT CDWs in a OS induced by a rotating field H_r ; (d) Magnetic potential well generated by the interaction of a magnetic particle and a CDW in an array of rings. Red and blue arrows depict the magnetic domain inside the rings.

unique aspect that differentiates these CDWs from DWs in a continuous film and makes them particularly attractive for particles nano-positioning is that, due to geometrical confinement, their spin structure is controlled by the lateral dimensions and thickness of the nano-conduit. In particular, for thin conduits (thickness $\ll$ width) the lateral width of a CDW is of the order of the strip width, and, therefore, can be easily compressed far below the micron scale by reducing the width of the conduit. Such CDWs are “spin blocks” that behave as quasi-particles and can be precisely displaced by playing with external fields and geometry.^[24,25] In a circular ring geometry, upon removal of the external field H_s , two CDWs nucleate and remain stable at the positions of nucleation that lie along the original direction of H_s . The resulting magnetic configuration shown in Figure 1(a), i.e., two magnetic domains separated by two oppositely aligned CDWs – one HH and the other TT – is commonly referred to as an onion-like state (OS). A second possible, field induced, magnetic configuration in a ring is a flux closure state, without CDWs, called vortex state (VS) and shown in Figure 1(b). The VS can be induced from a OS by the application of a reversal field H_v , viz., opposite to the one that induced the OS, that will cause the annihilation of the two CDWs.^[23]

Another peculiarity of CDWs is that they are a sort of “magnetic monopoles”, being a HH CDW a “north pole” and a TT

CDW a “south pole”.^[22,23] Therefore, CDWs generate an inhomogeneous magnetic stray field with a radial distribution, which for a HH CDW is directed outwards the CDW, with a positive out-of-plane component [$+z$ direction referring to Figure 1(d)]. Conversely, a TT CDW creates a stray field directed inwards the CDW and with a negative out-of-plane component ($-z$ direction). The coupling energy E , between the inhomogeneous stray field H_{DW} generated by a CDW and the magnetic moment μ of a nano-particle, defines an attractive potential well ($E = -\mu_0 \mu \cdot H_{DW}$). Owing to the superparamagnetic behavior of a nano-particle, and assuming for the sake of simplicity that the nano-particle is far from being saturated by H_{DW} , one can write $\mu = \chi H_{DW}$, where χ is the low field magnetic susceptibility of the nano-particle, which is a scalar quantity for the magnetically isotropic commercial beads considered here. Therefore, the coupling energy can be written as $E = -\mu_0 \chi H_{DW}^2$. The H_{DW}^2 dependence of E states that the strong field gradient generated by both a HH and TT CDWs can equally attract and trap a superparamagnetic fluid-borne nano-particle moving in the vicinity of either CDW. Once created, the two CDWs can be moved around the ring by applying smaller rotating magnetic field $H_r \ll H_s$, as shown in the schematic diagram in Figure 1(c). The magnitude of H_r is determined by the ring radius, width, and by the CDW local pinning due to the unavoidable fabrication defects in real samples. By rotating H_r , both the CDWs rotate synchronously and by the same angle, thus achieving a smooth, precise, and fully controllable CDWs displacement.^[15,22] A nano-particle magnetostatically coupled to a CDW will then move following the CDW displacement, which has been demonstrated in earlier studies, together with the attached biological cargo (proteins or even cells^[14,26]). An individual circular nano-ring is therefore performing the three main sought functions on a nano-particle: capture (nucleation of CDWs), local 2D manipulation (CDWs displacement around the ring), and release (CDWs annihilation).

Based on the manipulation capabilities achievable via the precise engineering of a magnetic ring size and shape, the central strategy of our approach is to devise a reliable and controlled way to exchange nano-particles among adjacent rings arranged on an matrix. Let's consider a nano-particle trapped by one of the two CDWs of a ring in the OS. When an external magnetic field H_{ext} is applied, the coupling energy equation given above can be rewritten as $E = -\mu_0 \mu \cdot H_{tot}$ where, $H_{tot} = H_{DW} + H_{ext}$. Thereby, the application of H_{ext} can be used to reshape the landscape of the coupling potential energy. Evidently, an $H_{ext} = H_z$ concordant to the z -component of H_{DW} will deepen the interaction potential well (i.e., strengthen the CDW trapping force), whilst an H_z discordant to H_{DW} will make it shallower (i.e., weaken the CDW trapping force).^[18] Likewise, it can be shown that an external in-plane field $H_{ext} = H_{x,y}$ would distort the trapping potential shifting its minimum away from the CDW, in the direction of H_{ext} .^[18]

Figure 2(a) shows the coupling potential energy landscape in a x - y plane at a constant height $h_z = 550$ nm, computed using OOMMF micromagnetic simulations^[27] and a MATLAB® code as described in the Supporting Information. The chosen value for h_z corresponds to the position of the center of the particle (we considered that the diameter of the particle is 1 μ m for simplicity) with respect to the ring surface including a 50 nm thick

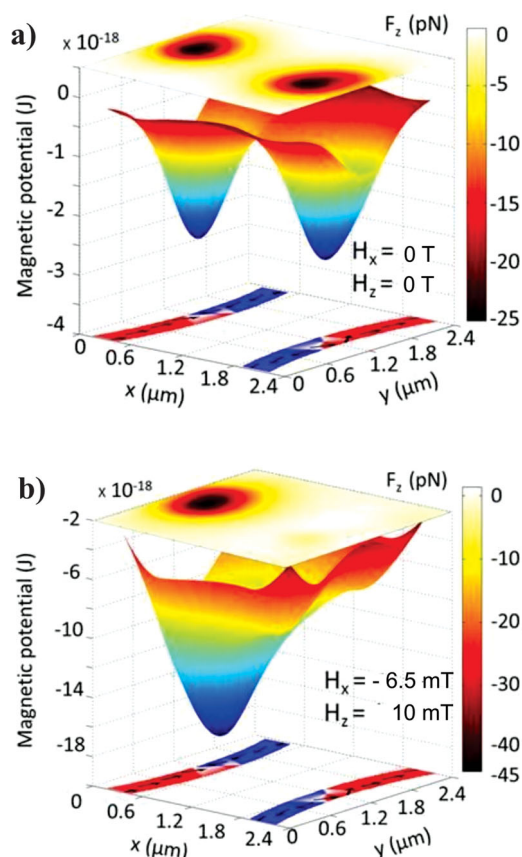


Figure 2. Magnetic potential energy felt by a $1\ \mu\text{m}$ bead, at $h_z = 550\ \text{nm}$, (a) In absence of H_z , the two CDWs of opposite polarity create the same potential well with a minimum of $-2.5 \times 10^{-18}\ \text{J}$; (b) When $H_x = -6.5\ \text{mT}$ and $H_z = 10\ \text{mT}$, the potential well generated by the HH CDW is largely enhanced up to $-16.0 \times 10^{-18}\ \text{J}$.

SiO_2 protective capping layer deposited on the ring surface in accordance to our experiments. In the absence of H_{ext} [Figure 2(a)] the energy landscape is a double potential well with its two minima on top of the two CDWs. Each minimum corresponds to a stable position for the magnetic particle due to the energy barrier that separates the two minima.

Assuming that the magnetic particle is initially trapped by the TT CDW, the new potential landscape resulting from the application of $H_{\text{ext}} = H_z + H_x$ has been calculated. Figure 2(b) illustrates the variation of the potential landscape for $H_z = +10\ \text{mT}$ and $H_x = -6.5\ \text{mT}$. As a result of the application of H_z and H_x , the potential well associated to the HH CDW is deepened, while at the same time, the potential well associated to the nearby TT CDW becomes shallower and the energy barrier between the original two minima is completely lifted out. The magnetic particle will therefore shift from its original position above the TT CDW towards the adjacent HH CDW. At this instance, if the

external fields H_{ext} is set back to zero, the symmetric double potential well with its energy barrier is restored and the particle remains in the new position, coupled to the HH CDW. Likewise, if the particle is initially trapped on top of the HH CDW, the application of $H_z = -10\ \text{mT}$ and $H_x = +6.5\ \text{mT}$ would cause the displacement of the particle towards the adjacent TT CDW.

Figure 2 also displays the intensity plot of the z -component F_z of the trapping force $\mathbf{F} = -\nabla E$, which is given by $\mathbf{F} = \mu_0 \chi \int_V (\mathbf{H}_{\text{tot}} \cdot \nabla) \mathbf{H}_{\text{tot}} dV$. In the absence of external fields, the attractive force F_z is approximately $17\ \text{pN}$ for both CDWs, which is in good agreement with previously reported values.^[28] By applying fields $H_z = +10\ \text{mT}$ and $H_x = -6.5\ \text{mT}$, the attractive force F_z generated by the HH CDW reaches a maximum value of $35\ \text{pN}$. A particle hopping along the y -direction is accomplished in the same way and requires only to rotate and align the CDWs along the y -direction and then apply a momentary external field $H_{\text{ext}} = H_z + H_y$. In summary, by using an array of circular rings and applying the suitable sequence of fields H_x , H_z , and H_{xy} , the local 2D manipulation on the individual ring is readily extended to the total surface of the device covered by the array.

The implementation of the selective trapping and release of particles requires an additional step: turning ON/OFF particle traps in desired portions of the device. This functionality requires, in turn, the controlled and robust generation of a VS in selected subsets of the array of rings. As anticipated before, a VS can be induced in a ring from a OS by the application of an external field causing the annihilation of the two CDWs of a OS.^[29–32] This process can be made more robust via the precise engineering of the ring shape. Here, this is achieved by designing magnetic asymmetric rings in which the mirror symmetry with respect to a selected in-plane axis is broken.^[24,33] The application of a momentary magnetic field along the selected in-plane asymmetry axis induces a transition from OS to VS, which remains stable once the external field is removed.

Figure 3(a) presents a SEM image of the two rings, one symmetric and one asymmetric, fabricated for illustrating this

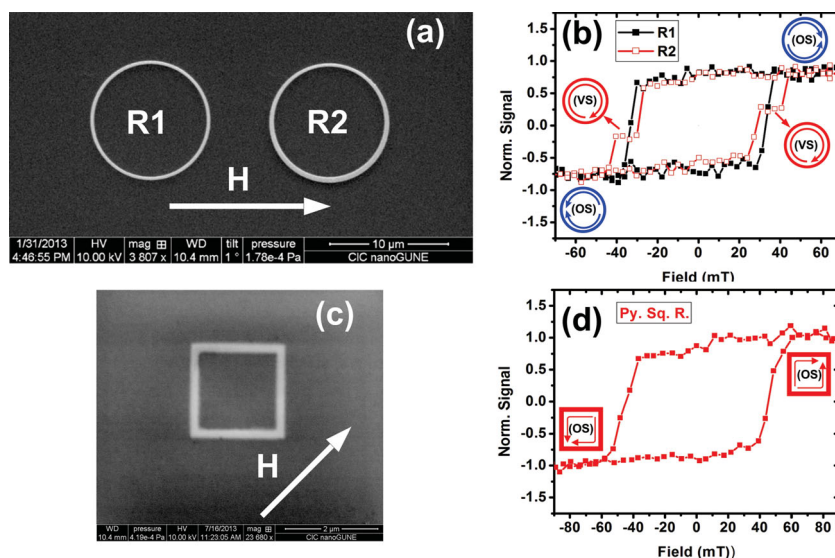


Figure 3. (a) SEM image of permalloy symmetric (R1) and asymmetric (R2) rings; (b) Hysteresis loops showing magnetization reversal in rings R1 and R2 for the external field H applied as indicated in the SEM image; (c) SEM image of single square ring; (d) hysteresis loop of the square ring for the external field H applied as indicated in the SEM image.

process. Both rings are made of $\text{Ni}_{80}\text{Fe}_{20}$ (Permalloy) and their thickness is 30 nm. The symmetric ring on the left (R1) has an outer diameter of 10 μm and a width of 200 nm, while the asymmetric ring on the right (R2) has the same outer diameter while its width varies gradually from 400 nm to 200 nm. In R2 the mirror symmetry is broken with respect to the in-plane horizontal axis. Figure 3(b) shows the hysteresis loops of an individual ring measured by using a magneto-optical Kerr effect microscope^[34] and applying a magnetic field along the horizontal direction. The asymmetry of R2 produces two distinct steps in the hysteresis loop, which are not present in the loop measured from R1. As sketched in the Figure 3(b), the steps at lower field values correspond to the transition from a OS to a VS and the steps at higher field values correspond to the nucleation of a reversed OS from the VS. The larger the asymmetry, *viz.* the difference between the widest and narrowest part of the ring, the higher is the field separation between the two steps in the hysteresis loop.^[24] The plateau between the two steps corresponds to the field range at which R2 is in a VS while a magnetic field is applied. The VS is frozen in the ring by reducing the external field to zero from any field value within this range. Noteworthy, the CDWs coherent rotation induced by a rotating field H_r when the ring is set to an OS is marginally affected by the asymmetry.

In the actual devices described and analyzed in this work, a subset of square rings has been introduced for the initial selective trapping of particles in a specific area of the device. The use of a different geometry, *i.e.*, square instead of circular, allows us to generate an OS, with a HH and a TT CDWs at two opposite corners of the square, which is stable in the range of field required to switch the state of the asymmetric circular rings between an OS and a VS and vice versa. Thereby, one can switch ON and OFF the magnetic traps in the asymmetric circular rings without affecting the CDWs of the square rings. Figures 3(c) and 3(d) show the SEM image and the hysteresis loop of such a square ring measured by applying an external field along the square diagonal. The square ring is made of Permalloy, its lateral dimensions are 2 $\mu\text{m} \times 2 \mu\text{m}$, its width is 150 nm, and the thickness is 30 nm. The hysteresis loop displays only individual jumps corresponding to the transition between reversed OSs, with CDWs, one HH and one TT, at the opposite corners of the square ring along the field direction. The comparison of the Figures 3(b) and 3(d) clearly shows that the OS in the square ring is stable in the field range (<40 mT) required to induce the transitions between an OS and a VS in the circular asymmetric rings. Therefore, the magnetic behavior of the two types of rings is completely decoupled, as desired.

Using the aforementioned dimensions for the circular (asymmetric) and square rings, two devices are designed and fabricated: (i) a chip where an individual square ring (an individual trapping site) is placed adjacent to an array of asymmetric circular rings (manipulation area) at a distance of 1.5 μm [SEM image Figure 4(a)]; (ii) a chip where a line of vertically aligned square rings is placed adjacent to the array of circular rings in order to define a sequence of multiple trapping sites [SEM image in Figure 4(b)]. The mirror symmetry of the asymmetric circular rings is broken with respect to the in-plane direction parallel to the diagonal at 45° of the square rings, as sketched in

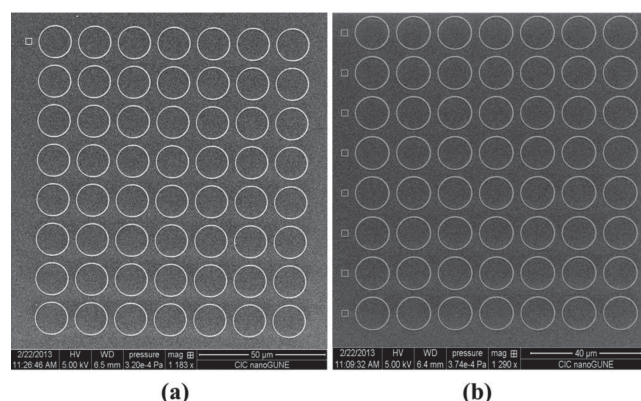


Figure 4. SEM images of the two device configurations investigated: (a) an array of asymmetric permalloy rings and single square ring placed at top left corner of the array; (b) An array of asymmetric permalloy rings and a line of square rings adjacent to the left hand side of the array rings.

Figure 5 where just a square ring adjacent to a circular one are displayed for illustration purposes.

Figure 5 sketches the steps we apply in the actual experiments to initialize the devices. Initially, an in-plane momentary magnetic field of $H_{xy} \approx 50$ mT is applied along an angle of 45° to create CDWs at the corners of the square ring. On the other hand, CDWs are nucleated simultaneously in all the circular rings as sketched in the Figure 5 (Step 1). In the second step, a reverse momentary field $H_{xy} \approx -30$ mT is applied at the same angle of 45° to create a VS in the asymmetric rings while retaining the two CDWs in the square ring (Figure 5, Step 2). In the third step, a stationary field $H_z \approx +10$ mT is applied to select a HH CDW at the upper right corner of the square ring as the only active trapping site (Figure 5, Step 3). In the fourth step, the solution with magnetic beads is injected on to the device surface while keeping H_z applied. After a few minutes, it was observed that an individual magnetic bead is trapped by the unique attractive potential at the selected upper-right corner of the square ring (Figure 5, Step 4). Thereafter, the device is flushed out to remove the beads in excess over the device surface. At this point, the stationary H_z field can be removed. In the fifth step, subsequent to trapping the magnetic bead at the selected CDW in the square ring, an in-plane magnetic field of $H_x \approx 25$ mT is applied to nucleate a OS in the circular ring with a TT CDW adjacent to the HH CDW in the square ring that has trapped the bead (Figure 5, Step 5). Finally in the sixth step, momentary fields $H_z = -10$ mT and $H_x = 6.5$ mT are applied in order to distort the double potential well of the two adjacent CDWs, and make the bead jumping onto the nearby TT CDW in the circular ring (Figure 5, Step 6). Henceforth, a rotating in-plane magnetic field of $H_r \approx 20$ mT is sufficient to move the CDWs in the asymmetric ring along its perimeter thereby manipulating the bead accordingly. The bead can be transferred to an adjacent ring (not shown in Figure 5) by simply stopping the rotation when opposite types of CDWs are aligned along either the x or y direction and applying momentary fields $|H_z|$ and $|H_{xy}|$ of 10 mT and 6.5 mT with the right polarity, respectively, as discussed above.

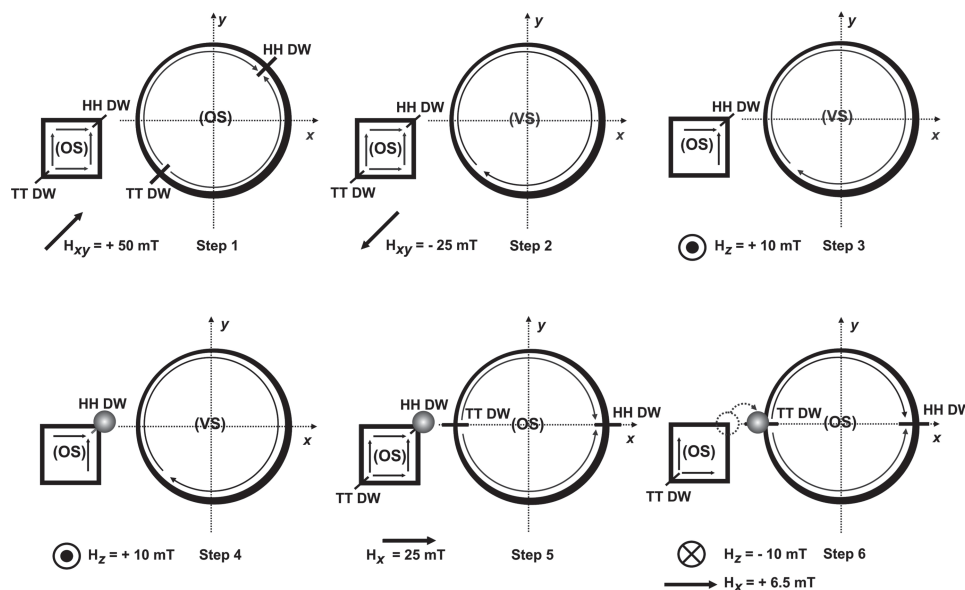


Figure 5. Schematics showing step by step the process for the initial field setup for single bead trapping and manipulation.

Figure 6 presents selected frames of videos recorded using an optical microscope equipped with a CCD camera, showing the programmable manipulation of (i) a single magnetic bead [Figure 6(b)–6(d)] and (ii) two beads [Figure 6(f)–6(h)] using the two devices displayed in Figures 4(a) and 4(b), respectively. In order to facilitate the utilization of the devices, a graphical interface is implemented that allows a user to draw the desired path on the real-time image provided by the CCD camera using the mouse of the computer connected to the camera, as shown in Figures 6(a) and 6(e). A LabVIEW code was developed to generate automatically a path code, viz., the sequence of fields H_r , H_z , and H_{xy} required to displace the selected bead along the desired path. Once the bead is moved to the desired position, it can be moved further or released by generating a VS in all the circular rings. In order to generate a path on the rings matrix, the only required input parameter is the initial trapping position (HH/TT CDW). For the videos presented here (see online supporting movie files, **SMV1** and **SMV2**), the in-plane magnetic field H_r is kept rotating in the clockwise direction since it simplifies the software to generate the field sequence. The actual path followed by the magnetic beads is therefore a sequence of arches shown as dashed lines in the video frames displayed in Figure 6(b)–6(d) and Figure 6(f)–6(h).

Strictly speaking, the devices described here do not allow for a truly 2-D manipulation since the diameter of the rings is much bigger than the size of the particle and therefore not any position on the manipulation surface is accessible. However, both the rings diameter and the particles size discussed here have been chosen only for

demonstration purposes in order to make it possible to follow the particles manipulation using an optical microscope. One property of magnetic rings that make them very appealing for various applications is their scalability without loss of performances: rings of submicron diameter can be nowadays fabricated and they are found to behave exactly the same as those, much bigger, utilized here. In addition, superparamagnetic particles of an arbitrary size can be manipulated. Indeed, the capture of individual nano-particles with diameter below 100 nm by a CDW in a ring was proven.^[35] All the above demonstrates that a truly 2-dimensional remote manipulation is indeed achievable with the approach proposed in this work.

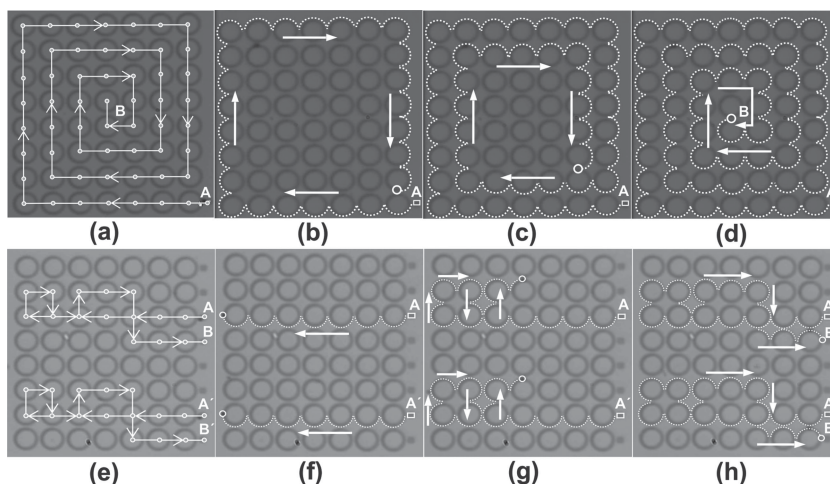


Figure 6. (a) Screen captured image of the device surface on which the desired path has been pre-defined from the initial position occupied by the bead 'A' to the final destination 'B'; (b–d) Frames of the captured video showing the programmable manipulation of a single magnetic bead, following the pre-defined path over the arrays of asymmetric permalloy ring matrix; (e) Pre-defined pathway drawn for multiple magnetic beads manipulation; (f–h) Frames of the captured video showing the programmable manipulation of multiple magnetic beads along the pre-defined path.

In conclusion, we have demonstrated and developed a novel device concept for a 2-dimensional remote manipulation of magnetic beads along any *arbitrary* pathway on a chip surface. The device operation relies on the field driven displacement of constrained domain walls in ring-shaped nano-scale ferromagnetic conveyors pre-patterned on a chip and their magnetostatic coupling with fluid borne superparamagnetic particles. We realized two test devices that prove the remote manipulation of individual and multiple magnetic nano-particles on a chip surface. The vastly extended manipulation capabilities offered by the devices concept described here together with the possibility to directly integrate CDWs conveyors into microfluidic devices recently established^[21] and the utilization of nano-particles as carriers of biomolecules and cells,^[26] open up a broad variety of new avenues in biology, medicine, chemistry, and even photonics, since nano-particles can be assembled on a surface remotely controlling the distance and symmetry of assembly for the realization of 2D colloidal photonic crystals with adjustable optical band gaps.

Experimental Section

The device is fabricated on Si (100) chip of 10 mm × 10 mm to manipulate magnetic beads on chip in solution. The electron beam lithography process was used to produce the magnetic ring structures. The desired pattern is drawn with the electron beam on electron sensitive resist layers previously spin-coated on Si (100) substrate. The electron sensitive resist we have used is a double layered Poly(methyl methacrylate) (DL PMMA) where the bottom and top layers are PMMA 450 K A4 with a thicknesses of 200 nm and PMMA 950 K A2 with thicknesses of 50 nm, respectively. To perform electron beam lithography, a RAITH 150^{TWO} tool is employed. The designed pattern on the DL-PMMA is generated using an acceleration voltage of 10 kV, a 10 μm aperture, and a measured current of 15 pA. The size of the write-field employed is 100 μm × 100 μm and the area dose is 100 μC/cm². Subsequent to developing the generated patterns, a Permalloy layer with a thickness of about 30 nm is electron-beam evaporated onto the generated patterns using an Oerlikon evaporator. Finally, the DL-PMMA is removed in a lift-off process, leaving the desired structure of Permalloy rings on the silicon substrate. Subsequently, the magnetic structure is covered with a 50 nm thickness of SiO₂ capping layer in order to protect the rings from the aqueous bead solution. The thickness of the capping layer has been selected to optimize the strength of the trapping field, preventing it from exceeding the external fields required for the manipulation of the magnetic beads.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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ADVANCED MATERIALS

Supporting Information

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Two-Dimensional Programmable Manipulation of Magnetic Nanoparticles on-Chip

*Anandakumar Sarella, Andrea Torti, Marco Donolato, Matteo Pancaldi and Paolo Vavassori**

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Two-dimensional programmable nano-manipulation of magnetic particles on-chip

*By Anandakumar Sarella, Andrea Torti, Marco Donolato, Matteo Pancaldi, and Paolo Vavassori**

Micromagnetic simulations using the OOMMF public platform: For the OOMMF simulations, we used superparamagnetic particles of 1 μm in diameter and the material properties (made of permalloy) of the rings are the same as the actual sample in terms of rings size & shape and separation distance between two rings. Simulations were carried out in the case of two permalloy rings with a 30 nm thickness, having an average diameter of 10 μm and a width of 300 nm, positioned at a relative distance of 1.5 μm along the x -direction. Since we are only interested in equilibrium states, the parameters taken include; permalloy cubic cell with a size of 10 nm, saturation magnetization M_s of 80 kA/m, no magneto-crystalline anisotropy and a damping coefficient $\alpha = 0.5$. The high scalability of the ring structure allows preserving its magnetic behavior upon reducing the diameter far below the micron scale. Therefore, the following findings hold true for real nm-scale rings and particles. Two contiguous CDWs- HH & TT are generated by applying a momentary magnetic field $H_x = 500$ Oe along the x -axis. Once the H_x field is removed, the field $H_{tot} = H_{DW}$ produced in the surrounding space (up to a height of 1100 nm above the nano-rings surface) by the two CDWs nucleated along the x direction in the adjacent branches of the rings is computed by OOMMF.

From H_{tot} , we have calculated the magnetic interaction potential well using MATLAB® between the CDWs and a superparamagnetic particle, which is similar to those used in the real experiment i.e., a diameter of 1 μm , magnetic susceptibility χ of 1.4 and magnetization at saturation M_s is 39 kA m^{-1} . The magnetic potential energy has been calculated through the expression: $E_b = -\mu_0 \int_V M_b \cdot H_{tot} dV$ where $M_b = m_b / V$ and m_b is the magnetic moment of the superparamagnetic bead of volume V induced by H_{tot} .

Magnetic beads and experimental setup: To visualize the magnetic bead manipulation through optical microscope, commercially available superparamagnetic beads of 1 μm diameter (purchased from myOne™, Invitrogen®) were used. The magnetic bead volume susceptibility χ is 1.44 higher than unity and its saturation magnetization M_s is 39 kA m⁻¹, which represents a good compromise between the most commonly used particles with a diameter ranging from 250 nm to 2.8 μm and the above bead specifications.

Figure S1 shows the experimental setup of the bead manipulation. A microfluidic cell made of Poly (dimethylsiloxane) (PDMS) is used to accommodate the Si chip with the designed device, which is positioned at the center of four computer controlled electromagnetic coils. Three Kepco® bipolar power generators were used to supply the current necessary for the 3-dimensional electromagnetic field generation. The out-of-plane H_z magnetic field is generated by a hollow cylindrical coil placed around the fluidic cell. The inner diameter of the coil is set large enough to let the microscope objective lens pass through the coil. The coil generates a low out-of-plane magnetic field of up to ≈ 100 Oe, which is sufficient to modify the potential landscape of the CDWs in the rings as discussed above. For imaging, we have used an optical microscope with a 20 $\times$ magnification objective lens (NA= 0.22) integrated with CCD camera, which allows for tracking the bead motion in a large area of several hundreds of microns.

Prior to the bead manipulation experiment, the micro fabricated device surface is blocked by a Phosphate Buffer Saline (PBS) solution with 1% w/v BSA and 1% v/v Triton X-100, in order to reduce the non-specific interaction & friction between the bead surface and the silicon substrate, and also to ease the manipulation over the magnetic rings. To prevent the clustering of magnetic beads, bead solution is prepared by diluting 1 μL of magnetic beads (concentration of 10 mg/mL), with a 30 % of PBS, 70 % of Deionized water and 0.5% of Triton X-100 to obtain a final concentration of 2 $\mu\text{g}/5\text{ mL}$ or 1 $\mu\text{g}/10\text{ mL}$. The device is then

inserted in a PDMS microfluidic cell and filled with diluted magnetic bead solution using micro pipette. The fluidic cell is covered with a cover glass of 0.17 mm thick to visualize the magnetic bead motion through optical microscope.

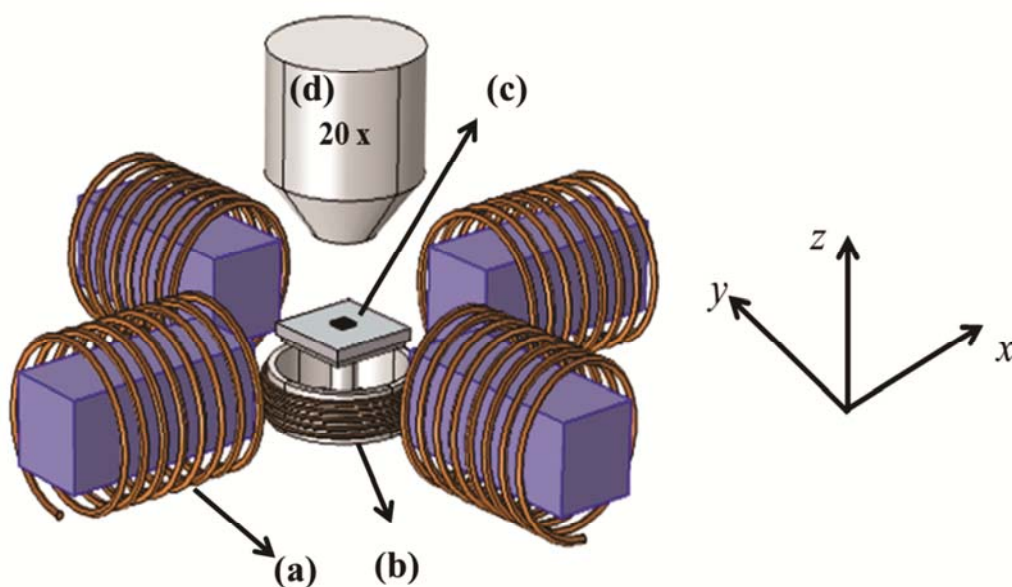


Figure S1. Schematic diagram of experimental setup used **(a)** four pole electromagnet for in plane magnetic field generation; **(b)** hollow cylindrical coil for out-of-plane magnetic field generation; **(c)** micro fluidic cell for bead manipulation; **(d)** optical microscope connected with CCD camera.