Easy Axis Dependence of Magnetic Vortex States of CrO_2 Nanodiscs

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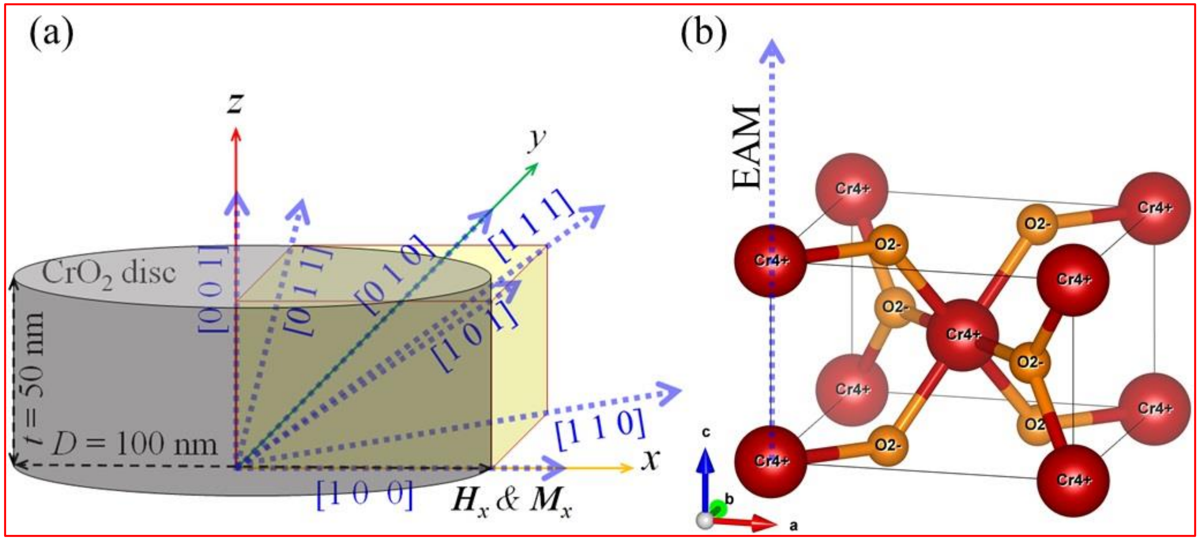
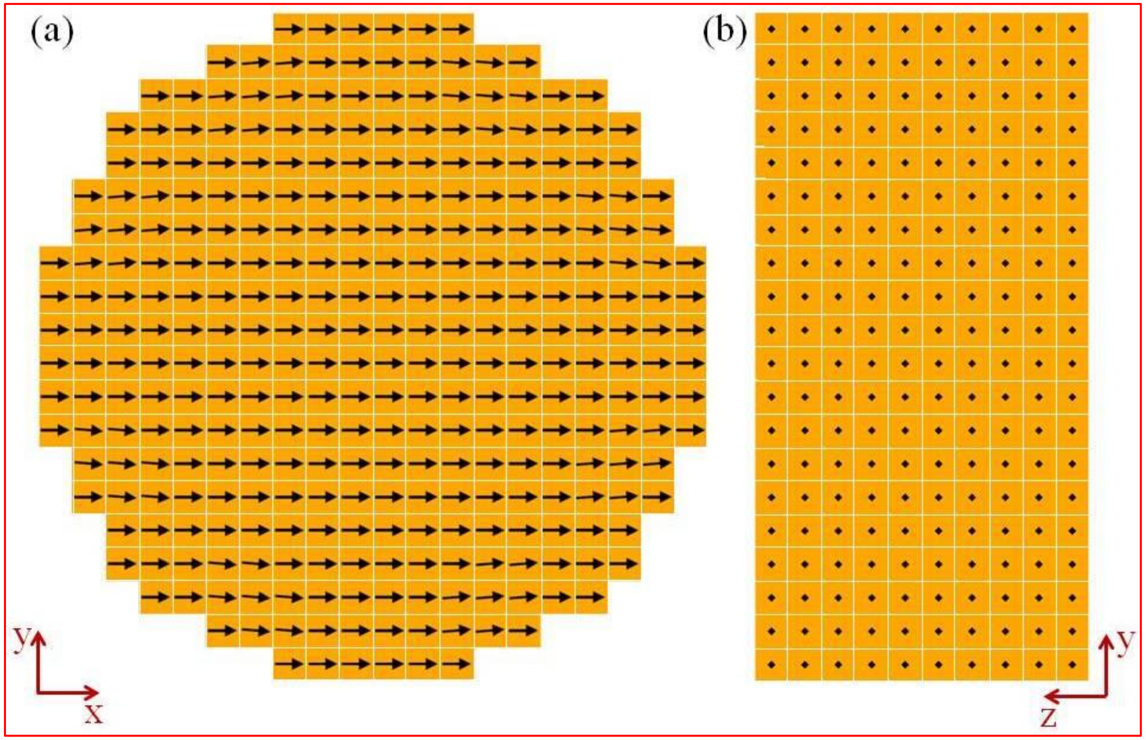
Material, method and model

Material:

- Most transition metal oxides are semiconductors or insulators.
- CrO_2 is a half-metallic ferromagnet; in which, the electrical current that pass through is spin polarized, even at room temperature!





Method: Object Oriented Micro-Magnetic Framework (OOMMF) software (version 2) from NIST, USA.

Model: CrO_2 nano-disc is modeled using $5 \times 5 \times 5\ nm^3$ cubic cells.

- The magnetization in each cell is described by *LLG equation*:

$$\frac{dM}{dt} = \gamma_G \left(M \times H\right) - \frac{\alpha_G}{|M|}\left(M \times \frac{dM}{dt}\right)$$

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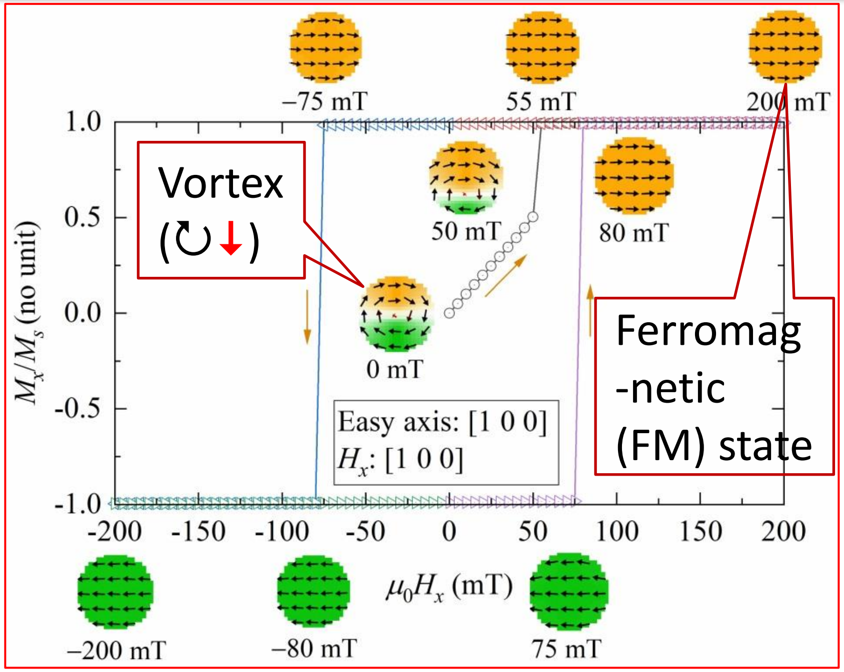
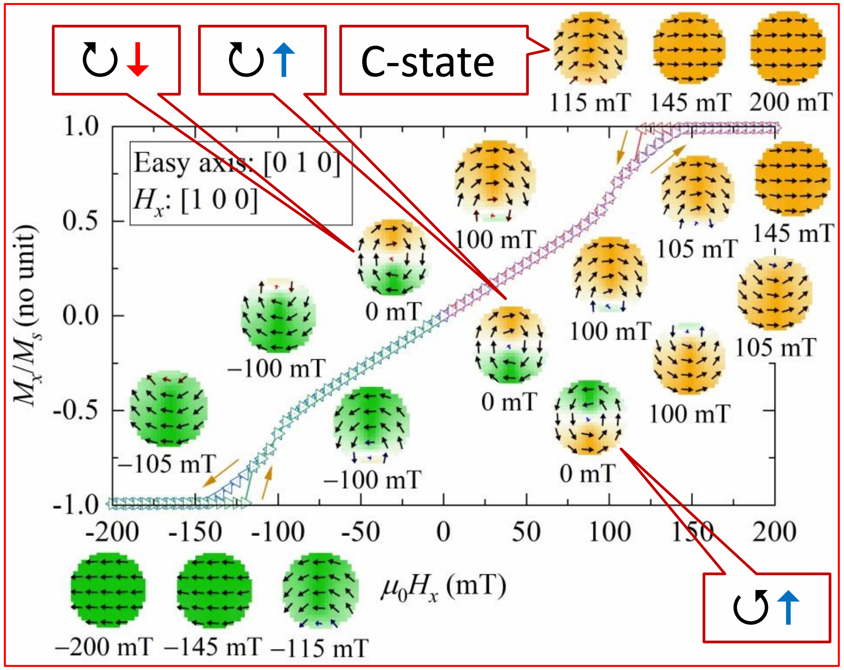
Magnetic hysteresis when the easy axis is along [1 0 0], [0 1 0] and [0 0 1]



Vortex (↻↓)

Ferromag-netic (FM) state



↻↓

↻↑

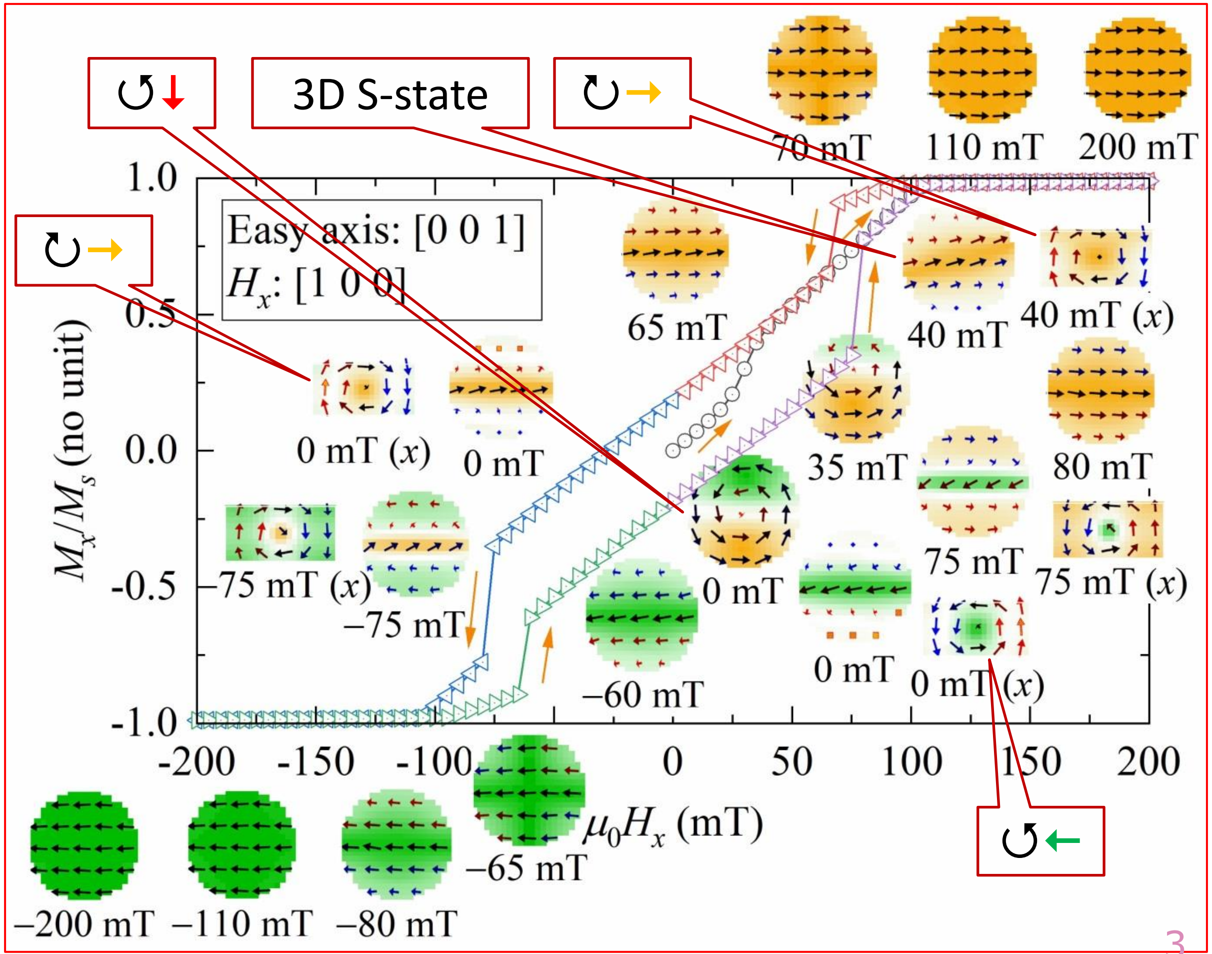
C-state

↺↑

Parameters for simulation: $M_S = 4.75\times10^5$ A/m

$A = 4.6\times10^{-12}$ J/m $K_1 = 2.7\times10^4$ J/m^3

- Gilbert damping parameter, α_G was set to 0.5 (for vortex formation) and an optimized value, 0.0023 (for vortex core switching).



↻↓

3D S-state

↻→

↻→

↺←

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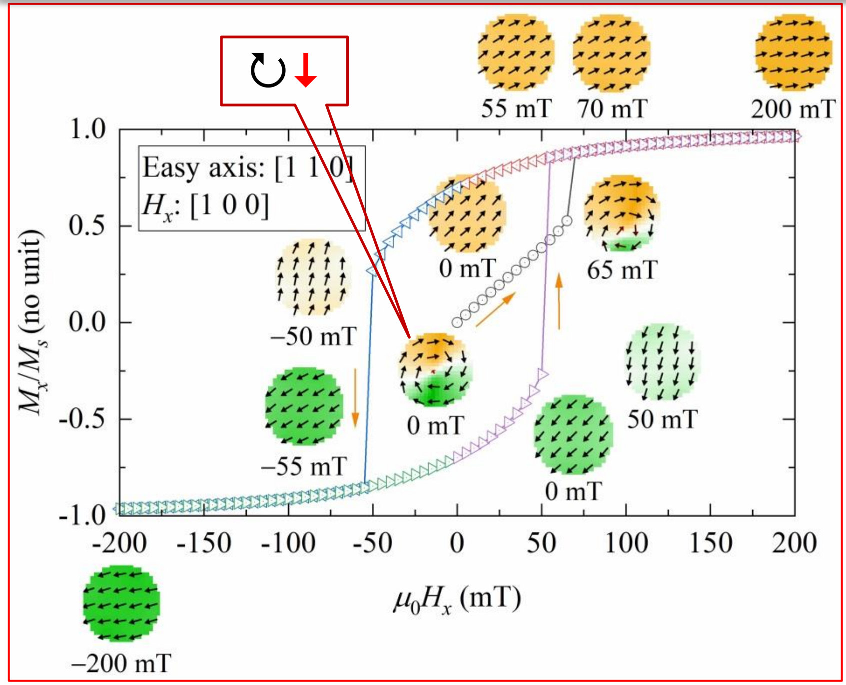
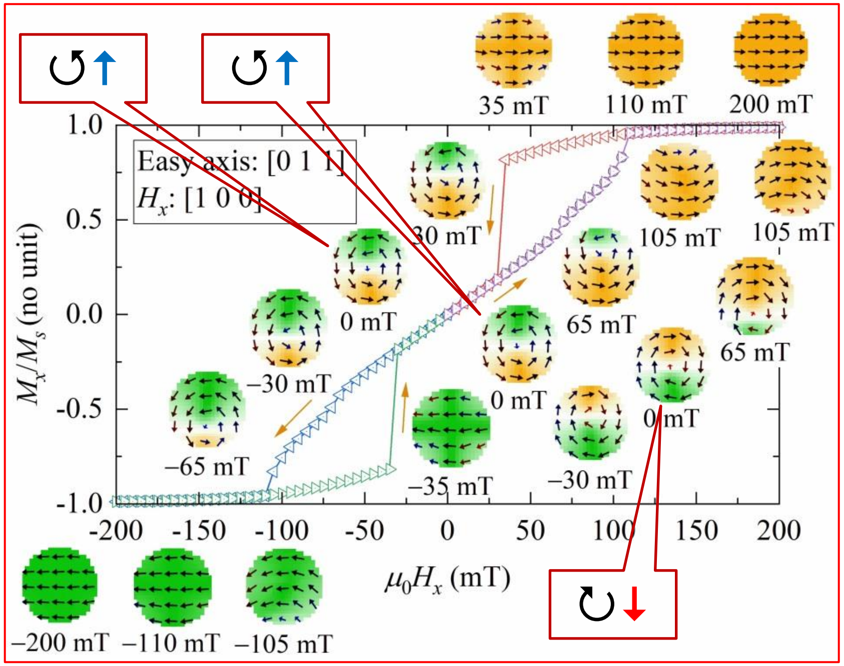
Magnetic hysteresis when the easy axis is along [1 1 0], [0 1 1], [1 0 1] and [1 1 1]

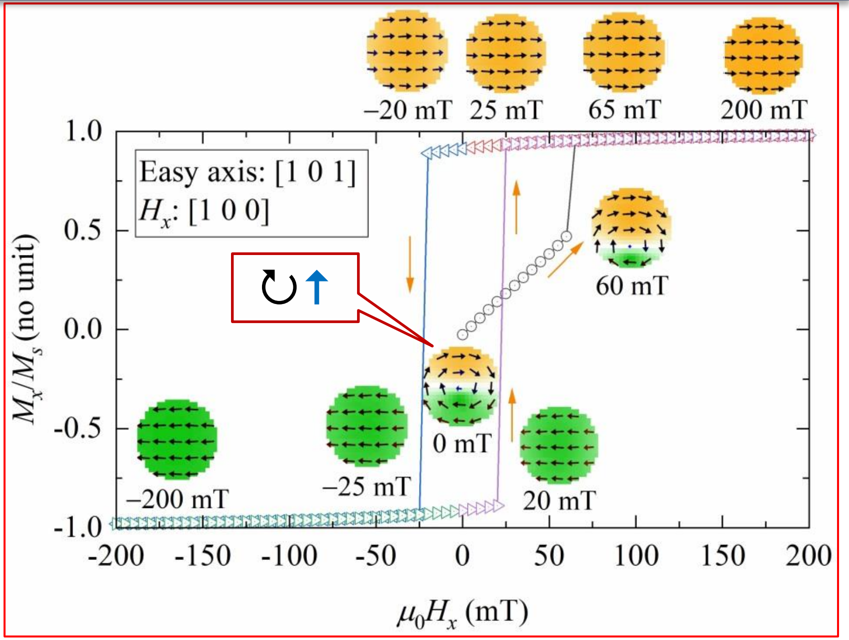


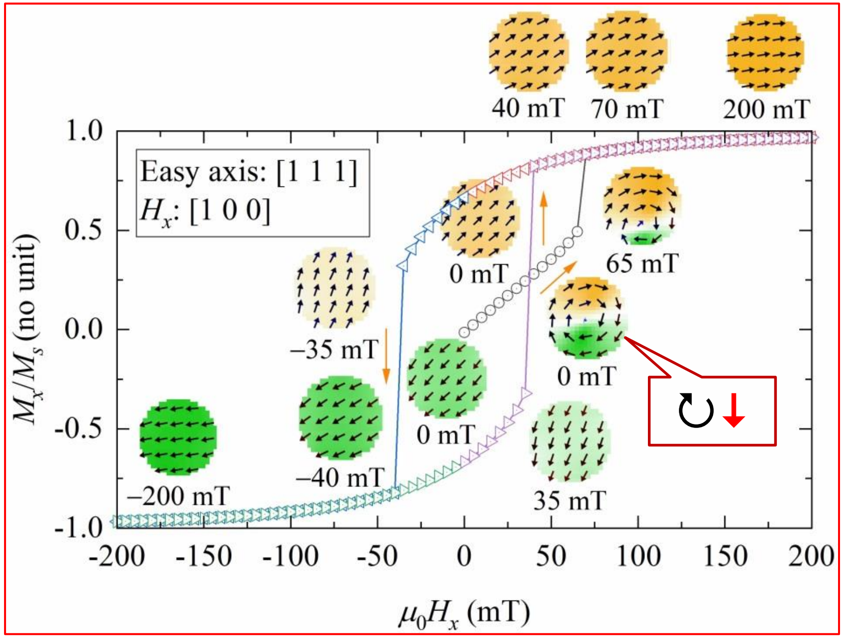


For the [0 1 0] and [0 1 1] easy axis orientations, the remnant states are **out-of-plane vortex** states☺.

For the [0 0 1] easy axis orientation, the remnant states are **in-plane vortex** states☺

For [1 0 0], [1 1 0], [1 0 1] and [1 1 1] easy axis orientations, the remnant are **not vortex** states☹





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Comparison of micro-magnetic properties when the easy axis is at seven different directions

The table given below summarizes the main results of micro-magnetic simulations performed for CrO_2 nanodiscs (of 100 nm diameter and 50 nm thickness) having its easy axis of magnetization oriented in various directions [*x y z*] with respect to the fixed direction of the external magnetic field applied along the *x*-axis.

S.No.	**Orientation of the easy axis [*x y z*]**	**H_{FP} (mT)**	**Magnetic vortex for**		**M_r/M_s**	**H_{sw} (mT)**
			Initial $H_x = 0$	**$H_x \neq 0$**		
1	[1 0 0]	55	Yes	No	0.9895	−80
2	[0 1 0]	145	Yes	Yes	0	N.A.
3	[0 0 1]	110	Yes	Yes, in-plane type.	0.1850	N.A.
4	[1 1 0]	70	Yes*	No	0.6991	$-55^{\$}$
5	[0 1 1]	110	Yes	Yes	0	N.A.
6	[1 0 1]	65	Yes	No	0.9136	−25
7	[1 1 1]	70	Yes*	No	0.6663	$-40^{\$}$

H_{FP}: The value of H_x at which the initial ferromagnetic parallel (FP) state is set up
H_{sw}: The value of H_x at which the ferromagnetic parallel (FP) state switches (reverses) by 180°
*Ellipse shaped magnetic vortices as initial, zero field ($H_x = 0$) states
$^{\$}$Magnetization switching happens by a gradual process followed by a steep jump

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Comparison with Permalloy nanodisc and Conclusion

For the external magnetic field applied along the *x*-axis, if the relative orientation of the easy axis of magnetization is at $\theta = 0°$ or any proximity of 45° (i.e., $0° \geq \theta \leq 55°$), the vortex states do not emerge; but, for any orthogonal orientations ($\theta = 90°$), magnetic vortex states emerges.

The below table[#] gives a comparison of the characteristics of magnetic vortex states of CrO_2 and permalloy nanodiscs of same dimension (100 nm diameter and 20 nm thickness)

Parameters	**Chromium(IV) oxide, CrO_2**	**Permalloy, $Ni_{80}Fe_{20}$**
Vortex nucleation field	12 mT	45 mT
Vortex annihilation field	41 mT	81 mT
Remnant sate (at 0 mT)	Magnetic vortex	Magnetic vortex
Core reversal using DC magnetic field	In ~14 μs at 138 mT	In ~739 μs at 189 mT
Eigen-frequency	6 GHz	14 GHz
Core reversal using AC magnetic field	0.32 ns for 50 mT	0.27 ns for 50 mT

The superior characteristics of the magnetic vortex states of CrO_2 nanodiscs make it useful for magnetic vortex based memory applications.

[#] *K. Balamurugan et al., J. Magn. Magn. Mater. 494 (2020) 165845.*

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