Statistical Behavior of Formation Process of Magnetic Vortex State in $\text{Ni}_{80}\text{Fe}_{20}$ Nanodisks

Mi-Young Im^{1*}, Peter Fischer¹, Yamada Keisuke², and Shinya Kasai^{2,3}

¹*Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley CA94720, USA*

²*Institute for Chemical Research, Kyoto University, Uji 611-0011, Japan*

³*Spintronics Group, Magnetic Material Center, National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan*

Magnetic vortices in magnetic nanodots, which are characterized by an in-plane (chirality) and an out-of-plane (polarity) magnetizations, have been intensively attracted because of their high potential for technological application to data storage and memory scheme as well as their scientific interest for an understanding of fundamental physics in magnetic nanostructures [1]. Complete understanding of the formation process of vortex state in magnetic vortex systems is very significant issue to achieve storage and memory technologies using magnetic vortices and understand intrinsic physical properties in magnetic nanostructures. In our work, we have statistically investigated the formation process of vortex state in permalloy (Py, $\text{Ni}_{80}\text{Fe}_{20}$) nanodisks through the direct observation of vortex structure utilizing a magnetic transmission soft X-ray microscopy (MTXM) with a high spatial resolution down to 20 nm [2]. Magnetic imaging in Py nanodots was performed at the Fe L_3 (707 eV) absorption edge. Figure 1 shows in-plane and out-of-plane magnetic components observed in 40 nm thick nanodot arrays with different dot radius of $r=500$ and 400 nm, respectively. Vortex chirality, either clockwise (CW) or counter-clockwise (CCW), and polarity, either up or down, are clearly visible in both arrays. To investigate the statistical behavior in formation process of the vortex state, the observation of vortex structure at a remanant state after saturation of nanodots by an external magnetic field of 1 kOe has been repeatedly performed over 100 times for each array. The typical MTXM images of vortex chirality taken in two successive measurements together with their overlapped images in nanodot arrays of $r=500$ and 400 nm are displayed in Fig. 2. Within the statistical measurement, the formation process of chirality of either CW or CCW is quite stochastic in each nanodot. Similar behavior is also witnessed in the formation of vortex polarity observed in consecutive experiments of the same arrays. Interestingly, a particular selectivity between the circulation sense of chirality and orientation sense of polarity for each other is found in the formation process of vortex state despite of their respective stochastic generation in repeated measurements. Dzyaloshinskii-Moriya (D-M) interaction in magnetic nanodisks, which is inevitably generated due to the breaking of inversion symmetry at surface/interface in magnetic thin layers [3], is mainly responsible for the experimentally witnessed selectivity between chirality and polarity in a formation of vortex structure.

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Fig. 1. MTXM images of in-plane and out-of-plane magnetizations observed in 40 nm thick Py nanodot arrays with different radius of $r=500$ and 400 nm. Here, the relatively dark (bright) contrast in Figs. 1(a) and (b) indicates the magnetization directed to left (right) and spot in the center of dots in Figs. 1(a') and (b') corresponds to the upward (downward) core magnetization.

Fig. 2. Images of vortex chirality taken in two successive measurements together with their overlapped images in Py nanodot arrays of $r=500$ and 400 nm. In overlapped images, clear vortex structure revealed in some nanodots indicates that the circulation sense of the vortex chirality in those nanodots is switched in repetitions.

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