A very specific spin configuration in magnetic nano-objects, known as a magnetic vortex in different shapes and dimension is promising for bio-applications, information-storage and processing technologies. For example, some literatures report the possibility of artificial structures of magnetic vortices in 2D nanodisks showing exotic physical phenomena. Additionally, magnetic vortex in a cubic or spherical shaped, instead of single-domain magnetic particles, may be exploited for bio applications, therefore, nanoparticles of 3D vortex could be of particular interest for dedicated purposes. Combining these results, self-assembly of isolated or aggregated magnetic nanoparticles is a promising approach to utilize nanostructures with multiple magnetic vortices as an elementary unit. From the perspective of bottom-up approach, the self-assembly of 3D magnetic vortices system can be understood by investigating inter-particle interaction of small clusters of vortex nanoparticles. However a precise knowledge of inter-particle interactions between magnetic-vortex particles is still elusive.

In the present study, we have clarified the magnetic interaction of the permalloy (Py) nanoparticles of 3D vortices as a primary mechanism of forming isolated-single and aggregated-double, triple, and quadruple spheres of different geometrical configurations. The Py nanoparticles of about 100 nm diameters were synthesized by the polyol method (Figure 1). From the transmission electron microscopy (TEM) analysis, preferred geometric configurations for the combination of Py particles were found depending on the number of assembled particles (Figure 2). With the help of micromagnetic simulations, the interparticle interactions between the corresponding assemblies were investigated. From the calculations, it is readily shown that magnetic exchange interaction acts as a key factor for forming assemblies of magnetic vortices. The spin configurations of specific assemblies were further investigated by off-axis electron holography (EH). We measured EH from isolated-single and interacting-triple particles of different arrangement. As expected from the micromagnetic simulation, the isolated 100 nm nanoparticles exhibited a vortex state. In the case of interacting particles, the direction of the vortex cores in assemblies is consistent with the calculations. Our results indicate that there is a controllable means of assembling complex nanoparticles of unique 3D vortex spin configuration.

Acknowledgement: This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (Grant No. 2013030460), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF 201304238).
Fig. 1: (a) TEM image of aggregated Py nanoparticles with diameter of 100 nm. (b) XRD pattern of Py nanoparticles with diameter of 100 nm. (c) SAED pattern of single nanoparticle. (d) Magnetic hysteresis loops of aggregated Py nanoparticles of 100 nm recorded at 300 K.

Fig. 2: TEM images of small self-assemblies of 100 nm Py nanoparticles. Observed assemblies are indexed by numerical number and alphabet.