

## 論文の内容の要旨

論文題目 Concept of magnetic artificial molecules by exploiting particle-like spin dynamics of coupled vortex structures (連結磁気渦構造における粒子的スピンドYNAMICSを用いた磁気人工分子のコンセプト)

氏名 杉本 聡志

Recent rapid progress of micro- and nanofabrication techniques in the last few decades has paved new ways for magnetism, and enabled us to discuss previously hidden parameter in conduction phenomena, spin of electrons. Such spintronics is worth to be said one of the hottest topic in modern science in past two decades. Especially in applicational area, the dynamic properties of ferromagnetic micro- and nanostructures have gained a broad scientific interest. Among them, analogous to electrons as a de Broglie wave in the periodic crystal potential form an energy band, the concept of the magnonic crystal (MC) is denoted as spin wave propagation in periodic ferromagnetic media. The MC is a subject of growing interest owing to its applications to spin wave waveguides, filters, phase shifters, and active oscillators. Due to a rich material selectivity and technological property of ferromagnets, many studies of magnonic crystal have been conducted so far.

Here a new type of MC is proposed exploiting coupled particle-like dynamics of the collective mode of vortex structures. Generally vortex structure as magnetization configuration is reliably stabilized in cylindrical shaped ferromagnetic dots or nano-point contacts as a remanent state usually even at room temperature, without any external magnetic field. The magnetic vortex shows resonant gyration of the vortex core around the equilibrium position at sub GHz frequency band named as the translational mode (TM) and this fixed core motion is approximated by rigid quasi-particle dynamics in the parabolic potential. Therefore, the magnetic vortex is unique model system to pick up particle-like dynamics from diffusively propagating spin dynamics. The magnetic dipolar interaction is adopted to couple different vortices confined in dot shaped soft ferromagnets by neighboring them with nanoscale interval distances.

In this thesis, two complementary approaches, frequency domain measurement exploiting magnetoresistance based rectification effect and time domain measurement of magneto optical Kerr effect have been demonstrated. Firstly, TM of the single magnetic vortex has

been experimentally investigated in the development process of both measurements. Obtained results can be quantitatively explained within approximation as a rigid quasiparticle dynamics, using so called Thiele equation. Full energy scheme of the dynamical process is calculated with the demagnetization energy and the exchange energy of ferromagnets. Further, the emergence of magnetic charges at side surface of ferromagnetic disks is introduced.

With insights of dynamics single vortex, the unit structure of these vortex used MC, two paired magnetic vortices with nanometer interval distances place in the same plane, has been investigated. Four different types of alignment have been demonstrated to extract relations of magnetization configurations and phases of core dynamics. The original eigen energy of TM takes the sole value independent from the chirality of magnetization configuration. Once magnetostatically coupled, such sole state spits into four distinctive states, forming two bonding and antibonding-like modes respectively, reflecting on degenerated two characteristics of vortex structure: polarities ( $p_i = \pm 1$  for up or down magnetization direction at core region) and chiralities ( $c_i = \pm 1$  for clockwise or counterclockwise in plane curling magnetization direction). Each coupled modes can be put in the framework of the actual molecules bound especially  $2p$ -orbitals of diatomic molecules. The stray field of vortices or electron cloud of  $2p$ -orbitals linearly distributes and spatial symmetry of these interactions decides the net energy of coupled system: possibly existing  $\sigma$ - and  $\pi$ -type bonding states as well as their anti-bonding states ( $\sigma^*$ - and  $\pi^*$ -type) showing a similarity  $2p$ -orbitals in diatomic molecules. This analysis results in analogous diagrams of energy schemes. Here, this unit of vortex based MC possess three notable properties may acceptable for use in expanded system. First, all energy levels uniquely labeled by polarities ( $p_1 p_2 = \pm 1$ ) and chiralities ( $c_1 c_2 = \pm 1$ ) and those are electrically switchable. Hence one can form the band structure which can be fully tuned by electrical method. Second, the energy dissipation of a dipolar coupled system has been estimated to be smaller than that of an exchange coupled system in continuous films, since the dipolar interaction is long range interaction. Time domain measurement of coupled system has revealed energy dissipation mechanism in coupled system is equivalent to original TM, implying expanded systems would never cause additional size effect on energy loss. Finally, this unit can be driven under the zero magnetic field and also at room temperature which is indispensable condition for modern magnetic devices.

The principle of magnetic diatomic molecules can directly be applied to larger molecular system consisting of two dimensionally arranged systems. The simplest demonstration of formation of a band structure has been investigated, 1-dimensionally coupled vortices. One can generalize the rules for paired vortices: coupled modes can be labeled by the anti-node number  $N$  of the standing spin wave as collective dynamics of TMs. In case of two vortices, in-phase gyration and opposite phase gyration correspond to  $N=1$  (uniform precessions) and  $N=2$  (opposite phase precession) respectively. Here, in case of three vortices, there exists uniform phase precessions ( $N=1$ ), precessions with neighboring phase difference  $\Delta\Phi = \pi/2$  ( $N=2$ ) and opposite phase precessions ( $N=3$ ). Increased numbers of vortices also increase possible anti-node numbers thus results in creating a continuous dispersion curve in

1-dimensional chain of coupled vortices, i.e. finite band width. The band structure of 1 dimensional MC of vortices can be tunable by switching polarities and chiralities. Switches of polarities change the interaction energy with neighboring vortices thus change the band width: the uniformly parallel polarities result in narrowest widths and fully anti-parallel ones cause widest widths here. Besides, Overall shape of band structure is affected by switches of chiralities. Therefore, these vortex-based MC should be a model case where both the directionality of wave propagations and band width are tunable simply by changing polarities and chiralities. Such new-type MCs might offer the advantages of limitless switchable-vortex-state and vortex-gyration-propagation endurance, low power signal input through resonant excitation of vortex gyrations, extremely low energy dissipation in information-processing devices when using negligible damping materials.