Phase diagram of the moving magnetic skyrmion lattice with plastic deformation in MnSi under high electric current

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A magnetic skyrmion is formed by a swirling spin texture. Such a swirling structure is characterized by a discrete topological number, called as skyrmion number. In the prototypical chiral magnet MnSi, magnetic skyrmions condense into triangular-lattice, observed as six-fold magnetic Bragg reflections in small-angle neutron scattering (SANS) [1]. In metallic skyrmion compounds, there is important characteristic, i.e., its surprisingly large coupling with the electric current flow. The electric current density required to realize the skyrmion lattice motion in chiral magnet MnSi is considerably small as $j_t \sim 1$ MA/m^2 [2]. Hence, the magnetic skyrmion in MnSi attracts growing attention recently, and is under intense scrutiny for elucidating its dynamical behavior under electric current. We performed SANS experiment in chiral magnet MnSi with suppressing thermal gradient as much as experimentally achievable. SANS experiments were carried out at NG7 in NIST and at QUOKKA in ANSTO. A direct electric current or an alternative electric current with square wave form was applied along the [0 0 1] direction. The sample mount was attached to the sample stick, and was installed in the horizontal field magnet with the magnetic field applied along [1 -1 0] parallel to the incident neutron beam. We observed the six-hold magnetic skyrmion reflections in the skyrmion phase under the electric current density $j = 0$. In the previous experiments, we found a spatially inhomogeneous counterrotating behavior of the magnetic skyrmion reflections measured at left-edge and right-edge above the threshold current density j_t [3]. The rotation direction of the magnetic skyrmion reflections can be inverted by the inversion of the electric current direction. In this time, we performed SANS experiment on the left-edge and right-edge of the MnSi sample under an alternative electric current flow to investigate a rotational dynamics of the magnetic skyrmion lattice. The size of the neutron illumination area is approximately 0.2 mm (width) × 1.0 mm (height). At the alternative electric current desnsity $j_{ac} > j_t$, the rotational motion of the magnetic skyrmion reflections follows an obvious alternative electric current frequency dependence. By the fitting of a naive Debye relaxation type function, we estimated the relaxation time t_r. In the frequency region of the alternative electric current below $1/t_r$, the rotational direction of the magnetic skyrmion reflections follows the inversion of the alternative electric current direction. In stark contrast, the magnetic skyrmion reflections do not respond when the frequency of the alternative electric current is higher than $1/t_r$. These results indicate that magnetic skyrmion lattices under current flow experience significant friction near the sample edges, and the rotational motion of the magnetic skyrmion reflections shows Debye type relaxation under the alternative electric current. Such a dynamics information of the magnetic skyrmion lattice being important factors that must be considered for the anticipated skyrmion-based applications in chiral magnets at the nanoscale. In summary, we have used SANS to study skyrmion-lattice motion in chiral magnet MnSi under an alternative electric current flow. The frequency dependence of the rotation motion of the magnetic skyrmion reflections was measured under an alternative electric current density $j_{\mathrm{ac}} > j_{\mathrm{t}} \sim 1\ \mathrm{MA/m^2}$.

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