Monte Carlo study of interacting magnetic nanoparticles with cubic magnetocrystalline anisotropy

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Much effort has been directed to develop growth techniques to combine ferromagnetism and semiconducting properties of the matter. One strategy is to create ferromagnetic semiconductors – typically of III-V groups: GaAs:Mn or GaN:Mn and GaN:Fe with the concentration of magnetic ions high enough to approach room temperature ferromagnetism. Unfortunately, these attempts usually result in the formation of ferromagnetic precipitations. The other strategy is to use thermal annealing, for instance applied to $Ga_{1-x}Mn_xAs$ layers which leads to formation of ferromagnetic MnAs dots, as well as that in MOVPE-grown (Ga,Fe)N ferromagnetic FeN_x nanocrystals aggregate by precipitations. Such mixed system of ferromagnetic grain in semiconductor host is often called nanocomposite: potentially promising candidate for information storage and spin electronics applications.

The problem, which occurs, is that such complex systems need theoretical modeling different than just simple virtual crystal approximation. For instance when modeling ferromagnetic (or superparamagnetic) properties it is necessary to include crystalline anisotropy of single-crystal domains within each ferromagnetic nanoparticle as well as its interaction with external magnetic field and other nanoparticles randomly distributed in space.

Monte Carlo method was used to study magnetic properties of an ensemble of randomly oriented, spherical, single-domain magnetic nanoparticles with cubic anisotropy. The model includes dipole-dipole interparticle interactions, magnetic anisotropy, and the effects of particle volume and interparticle distances. Hysteresis loops, zero-field-cooled as well as field-cooled magnetization curves were calculated for both negative and positive values of magnetic crystalline anisotropy constants (K1 and K2). It is observed that positive anisotropy constants result in much broader hysteresis loops and considerably higher blocking temperatures than in the case of negative ones. Strong dipole-dipole interactions suppress both the coercive field and the remanent magnetic moment of densely packed nanoparticles. This effect quickly disappears with increasing interparticle distances and becomes insignificant for separations exceeding, roughly, three particle diameters. The results are compared to experimental measurements of cobalt nanoparticles performed by SQUID magnetometry.

The reported results can be of interest from both a theoretical and an experimental point of view and they can be supportive in the interpretation of magnetic behavior of systems with cubic magnetocrystalline anisotropy. They can also inspire engineering new nanocomposite magnetic materials.