«Ferromagnetic inverse opal-like crystals – three-dimensional nanoanalogues of spin ice»

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Presented works are devoted to studying of magnetic and structural properties of cobalt and nickelinverse opal-like crystals by a combination of complementary techniques ranging from polarized neutron scattering and superconducting quantum interference device magnetometry to x-ray diffraction and ferromagnetic resonance.

Inverse opal-like structures (IOLS) were produced by filling the voids of an artificial opal film with Co or Ni by chemical electrodeposition.Then initial opal-like template has been dissolved in toluene.

The structure of inverse opal crystals was probed on the mesoscopic and atomic levels by scanning electron microscopy and synchrotron microradian and wide-angle diffraction. Microradian small-angle x-ray diffraction shows that the IOLS fully duplicates the three-dimensional net of voids of the template artificial opal. The inverse OLS has a face-centered cubic (fcc) structure with a clear tendency to a random hexagonal close-packed structure along the <111> axes.The diffuse scattering data were used to map defects in the fcc structure as a function of the number of layers in the Ni inverse opal-like structure. The average lateral size of mesoscopic domains is found to be independent of the number of layers. 3D reconstruction of the reciprocal space for the inverse opal crystals with different thickness provided an indirect study of original opal templates in a depth-resolved way.

The microstructure and thermal response (expansion coefficient and Debye temperature) of the framework of the porous inverse opal crystals was examined using wide-angle powder x-ray diffraction.It shows that the atomic cobalt structure is described by coexistence of 95% hexagonal close-packed and 5% fcc phases, while nickel IOLS is built fromfcc nickel crystallites possessing stacking faults and dislocations peculiar for the nickel thin films.Thermal parameters are also equivalent to those of nickel films.

The evolution of the magnetic structure for Co inverse opal-like structure under an applied magnetic field is studied by small-angle neutron scattering. It is shown that the local configuration of magnetization is inhomogeneous over the basic element of the inverse opal-like lattice structure (IOLS) but follows its periodicity. Applying the “ice-rule” concept, requiring magnetic flux conservation in each node of the IOLS, we describe the local magnetization of this ferromagnetic three-dimensional lattice. We have developed a model of the remagnetization process predicting the occurrence of an unusual perpendicular component of the magnetization in the IOLS which is defined only by the strength of the magnetic field, applied along [1-21] axis.This model also predicts the absence of a long-range magnetic order in two <111> directions that are normal to the magnetic field, when the latter is applied along [-110] axis. It is shown that magnetic neutron scattering contribution is close to zero over the entire applied magnetic field range for all scattering planes that are normal to the field, which agrees well with the proposed model.

The remagnetization curves of total magnetization M(H) and temperature dependences M(T) in the ranges of H from –50 to +50kOe and T = 5–350 K are measured by magnetometry using a superconducting quantum interference device (SQUID-magnetometry). It is demonstrated that at $T > 70$ K, the total magnetization of the inverted nanostructures is composed of four local magnetizations, the vectors of which are oriented along the <111>

anisotropy axes of a spatial opal-like structure. At low temperatures, the anisotropy of the film is found to make an additional significant contribution. The critical magnetic fields corresponding to reorientation of the local magnetization vectors along the <111>anisotropy axes are determined from the M(H) experimental curves. The data obtained for ferromagnetic inverted opal-like nanostructures are compared with the behavior of magnetization in continuous nickel and cobalt films.

In addition to experimental methods micromagnetic simulation has been exploited. The results of these calculations successfully confirmed the assumptions, made using phenomenological “ice-rule” and observed in experiments. Besides that, some new features of the IOLS magnetic behavior have been detected. In particularly changing in remagnetization procedure depending on the sintering degree has been obtained.

In fact, presented publications present the methodology of complex study of structural and magnetic properties of three-dimensional mesostructured ordered ferromagnetic systems.