**«Structural and magnetic properties of ferromagnetic inverse opal-like crystals»**

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Presented works are devoted to studying of magnetic and structural properties of cobalt and nickel inverse 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 toulene.

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 from fcc 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.

Investigations of microwave properties of Ni-based inverse ferromagnetic opal-like ﬁlm have been carried out in the 2–18 GHz frequency band. We observed multiple spin wave resonances for the magnetic ﬁeld applied perpendicular to the ﬁlm, i.e., along the [111] axis of this artiﬁcial crystal. For the ﬁeld applied in the ﬁlm plane, a broad band of microwave absorption is observed, which does not contain a ﬁne structure. The ﬁeld ranges of the responses observed are quite different for these two magnetization directions. This suggests a collective magnetic ground state or shape anisotropy and collective microwave dynamics for this foam-like material. This result is in agreement with SQUID measurements of hysteresis loops for the material, showed strong easy-plane anisotropy. Two different models for this collective behavior are suggested that satisfactorily explain the major experimental results.

The remagnetization curves of total magnetization M(H) and temperature dependences M(T) in the ranges of H from –50 to +50 kOe 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.