High performance permanent magnets without critical elements

Research Project Outline for 2nd Phase（FY2016–2018）

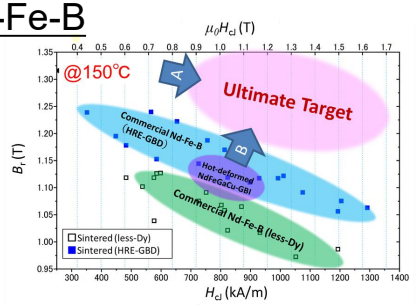
Permanent magnets with ultimate performance beyond Nd-Dy-Fe-B

I. Realization of ultimate magnetic performance

II. Search for and realization of Fe-based magnets

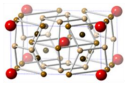
III. Establishment of basic science of permanent magnets

Ⅳ. Feeding industry with ESICMM basic research outputs



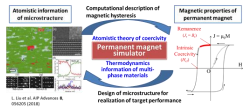
A: Compounds with large Fe content

RFe_{12}-type compounds



B: Optimization by materials science

Ab-initio predictions



Research Results (FY2016–2018)

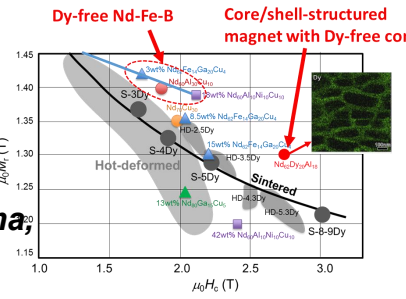
◆ Development of Dy-free Nd-Fe-B lead by analyses of coercivity mechanism

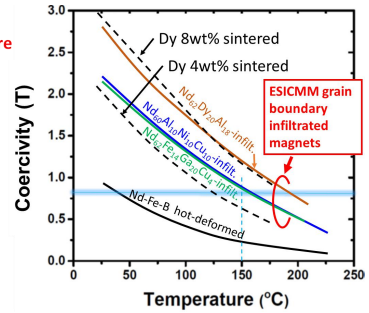
- Alloys with ferromagnetic 3d elements, Fe and Ni, in alloys for grain-boundary infiltration to realize high remanence
- Improved temperature dependence of coercivity to realize 150ºC durability without Dy (Hono, Ohkubo)

Dy-free Nd-Fe-B magnets

L. Liu, H. Sepehri Amin, T. Ohkubo, M. Yano, A. Kato, N. Sakuma, T. Shoji, K. Hono, Scripta Materialia 129, 44-47 (2017).

L. Liu, H. Sepehri-Amin, T.T. Sasaki, T. Ohkubo, M. Yano, N. Sakuma, A. Kato, T. Shoji, K. Hono, AIP Advances 8, 056205 (2018)





Magnetic properties of developed materials

◆ Synthesis of 1-12 type compound superior to Nd-Fe-B

- Synthesis of $Sm(Fe_{0.8}Co_{0.2})_{12}$ lead by ab-initio predictions.
- J_S =1.78T and $\mu_0 H_A$ = 12T exceeds those of $Nd_2Fe_{14}B$.
- Generation of 0.8T coercivity by Cu intergranular diffusion in thin films.
- Identification of Sm-Zr-Fe-Co-Ti compositions for bulk processing.

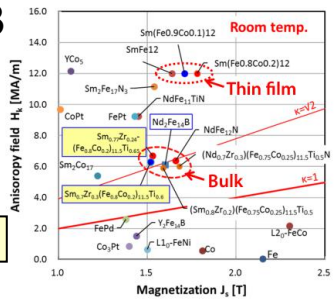
(Miyake, Hono, Takahashi)

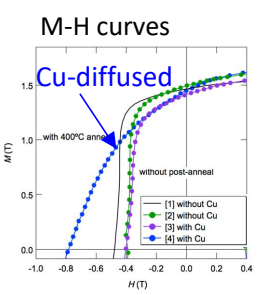
New material $Sm(FeCo)_{12}$

Y. Harashima, et al. J. Appl. Phys. 120, 203904 (2016)

Y. Hirayama, Y.K. Takahashi, et al. Scripta Mater. 138 (2017) 62

P. Tozman, H. Sepehri-Amin, et al. Acta Mater 153, 354-363, (2018)





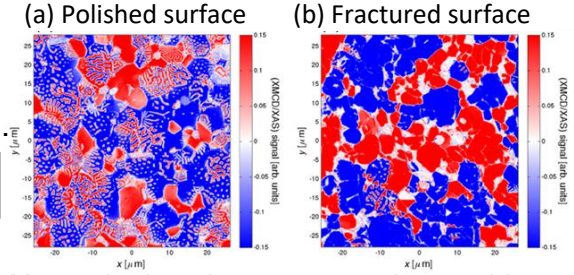
Magnetic properties of 1-12 type $Sm(Fe_{1-x}Co_x)_{12}$, Sm-Zr-Fe-Co-Ti, and other compounds

◆ Novel technologies for observation and analysis of demagnetization behavior

- Developed synchrotron soft X-ray nano beam element-sensitive scanning microscopy to reveal undisturbed magnetic domains
- Established FORC method to reveal distribution of domain wall depinning force.
- First-principles calculations to reveal interface structure and magnetism there-in.

(Nakamura, Okamoto, Gohda) Synchrotron X-ray magnetic microscopy

Y. Kotani, et al. J. Synchrotron Rad., in print.
T. Yomogita, S. Okamoto, et al., J. Magn. Magn. Mater. 447, 110-115 (2018)
Y. Tatetsu, et al. Phys. Rev. Appl. 6 (2016) 064029



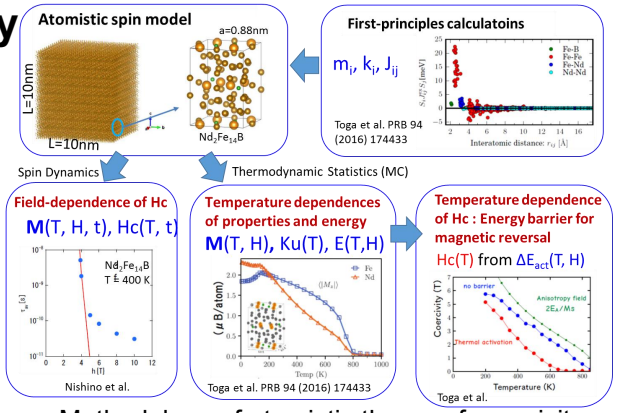
Magnetic domain structures observed by soft X-ray scanning magnetic microscope

◆ Theory of high-temperature magnetism and coercivity

- Atomic spin model of $Nd_2Fe_{14}B$ based on *ab-initio* calculations to describe temperature dependence of magnetization and anisotropy energy
- Determination of energy barrier for non-uniform magnetization process
- Calculation of stochastic magnetization process under thermal noise

(Miyake, Miyashita) Atomistic theory of coercivity

Y. Toga et al. Phys. Rev. B 94, 174433 (2016).
M. Nishino, Y. Toga, S. Miyashita, H. Akai, S. Hirosawa, Phys. Rev. B 95, 094429 (2017).
S. Miyashita, et al. , Scripta Mater. 154, 259 (2018)



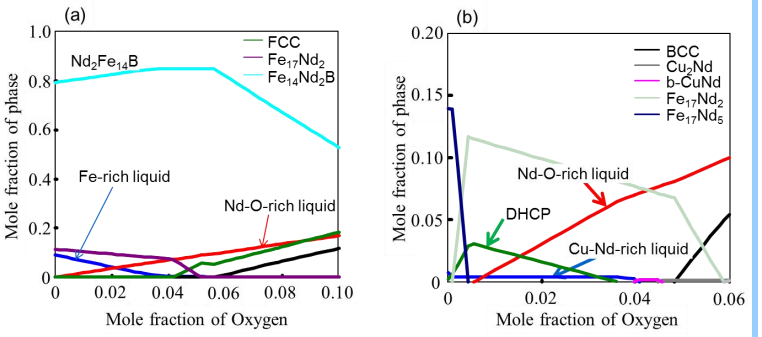
Methodology of atomistic theory of coercivity

◆ Thermodynamics database and computations

- Combining of equilibrium experiments and ab-ignition calculations
- Extension of database to a five-component Nd-Fe-B-Cu-O system
- First-time analysis of oxygen dissolved in Nd and Nd-rich liquid phases

(Abe, Koyama, Chen, Saengdeejing) Thermodynamics of multi-component rare earth magnet alloys

T. Oshino, Y. Kobayashi, T. Koyama, Mat. Trans. 57, 1771 (2017)
T. Abe, Y. Chen, A. Saengdeejing, Y. Kobayashi, Scripta Mater. 154, 305 (2018)



Computed phase diagram of Nd-Fe-B-Cu-O, enabling elucidation of the role of oxygen at 1100ºC (a) and 600ºC for the 1st time.