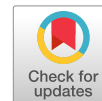


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First-principles study on surface stability and interface magnetic properties of SmFe_{12}

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We report the most stable surface of SmFe_{12} and the interface magnetic properties of SmFe_{12} with SmCu and bcc Fe as subphases. We find that the (110) surface with the highest exposition of Sm is the most stable surface of SmFe_{12} . Stabilization by the exposition of rare-earth is also confirmed for $\text{Nd}_2\text{Fe}_{14}\text{B}$. Moreover, we also demonstrate that SmCu improves not only magnetic moments and the anisotropy of grain surfaces of SmFe_{12} but also well suppresses the magnetic interaction between SmFe_{12} grains. © 2020 The Japan Society of Applied Physics

Ferromagnetic rare-earth compounds with the tetragonal ThMn_{12} structure have been seen as a promising main phase of permanent magnets becoming a successor to $\text{Nd}_2\text{Fe}_{14}\text{B}$, due to their magnetic properties comparable with or exceeding those of $\text{Nd}_2\text{Fe}_{14}\text{B}$.^{1–3)} In particular, among $R\text{Fe}_{12}$ (R : rare-earth element) compounds, the samarium-based compound SmFe_{12} with a particularly large anisotropy field^{4–6)} is a potential candidate for the main phase of permanent magnets. However, the binary SmFe_{12} compound has a problem that the bulk phase is thermodynamically unstable.^{7,8)} Previous experiments reported the stability is ensured by the partial substitution of Fe atoms in SmFe_{12} with nonmagnetic third elements such as Ti, V, Mn, Co, and Zn.^{8–14)}

On the other hand, as effects of microstructures, local magnetic properties including the anisotropy of rare-earth elements in the main phase close to interfaces are greatly affected by the physical properties of subphases, e.g. the crystal structure, the chemical composition, and the magnetism. In particular, those of the interfacial first layer are significantly different from the bulk state.^{15,16)} Thus, in order to realize the permanent magnets with the magnetic properties superior to the existing ones, it is necessary to understand the local magnetic properties of the interfaces on the atomic scale. Moreover, for the sake of the realization of the high coercivity, the suppression of the magnetic interaction between the main-phase grains by nonmagnetic subphases is needed.¹⁷⁾ The partial substitution of Fe atoms with nonmagnetic elements to stabilize SmFe_{12} often causes regrettably the precipitation of ferromagnetic α -Fe.^{8,14,18–20)} In the case of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$, recent investigations have proposed the possibility of avoiding the α -Fe precipitation by introducing Sm–Cu phases, particularly SmCu .²¹⁾ These new findings should also suppress the α -Fe precipitation for SmFe_{12} , due to the fact that the chemical composition of $\text{Sm}_2\text{Fe}_{17}$ is close to that of SmFe_{12} , and SmCu has been observed in computational study of the Sm–Fe–Cu phase diagram.²²⁾ In this sense, SmCu may be a promising candidate for a subphase of Sm-based permanent magnets with SmFe_{12} as the main phase.

As mentioned above, the magnetic properties of the permanent magnets are closely related to the electronic states of interfaces between the main phase and a subphase. In order

to reveal the electronic states of interfaces, interfacial atomic configurations are needed. To accomplish this, it is first and foremost required to identify surface structures of main-phase grains, because microstructure interfaces are usually formed by the solidification of a subphase on surfaces of the main phase. However, such surface atomic structures of SmFe_{12} as well as of $\text{Nd}_2\text{Fe}_{14}\text{B}$ are yet to be investigated.

In this paper, we first identify the most stable atomic configurations of SmFe_{12} surfaces. We find surfaces with the highest exposition of the Sm atoms is found to be most stable. Surfaces of $\text{Nd}_2\text{Fe}_{14}\text{B}$ are also examined, and the same trend is observed. We clarify that this surface stabilization by the exposition of rare-earth atoms comes from weaker chemical bondings of $5d$ states of rare-earth atoms compared with those of $3d$ states of Fe atoms, which minimizes the loss of the band energy of d electrons. Second, we investigate the magnetic properties of $\text{SmFe}_{12}(110)/\text{SmCu}(100)$ and $\text{SmFe}_{12}(110)/\text{Fe}(001)$ interfaces. We find that SmCu enhances the magnetic moments of the main-phase Fe atoms located near the interface to approximately $2.49 \mu_B$. The reason for this enhancements is a decrease in the hybridization between $3d$ states of the Fe atoms compared with that of the SmFe_{12} bulk, which is combined with the charge neutrality for $3d$ states of the Fe atoms. The improvement of the anisotropy of Sm atoms at interfaces are also observed. In addition, we quantitatively evaluated the effective exchange-coupling constant between the main-phase grains. The results show that SmCu well suppresses the magnetic interaction between the main-phase grains compared with ferromagnetic α -Fe.

Our first-principles calculations of surfaces and interfaces are based on density function theory using pseudopotentials and pseudo-atomic-orbital basis functions as implemented in the OpenMX code.²³⁾ In all calculations, the Perdew–Burke–Ernzerhof exchange-correlation functional²⁴⁾ within the generalized-gradient approximation was adopted. As basis sets, $s2p2d2$ configurations were used for Sm, Nd, Fe, Cu, and B with cutoff radii of 8.0, 8.0, 6.0, 6.0, and 7.0 Bohr, respectively. Semicore orbitals of $3s$ and $3p$ in Fe and Cu as well as $5s$ and $5p$ in Sm and Nd were treated as valence electrons. Open-core pseudopotentials were used for Sm and Nd atoms, where $4f$ electrons were treated as spin-polarized core electrons. As for convergence criteria, the maximum



force on each atom and the total-energy variation are 10^{-4} Hartree/Bohr and 3.1×10^{-9} Hartree/atom for surface calculations, and 10^{-3} Hartree/Bohr and 1.3×10^{-7} Hartree/atom for interface calculations, respectively. The lattice parameters were set to $a = b = 8.54 \text{ \AA}$ and $c = 4.71 \text{ \AA}$ for SmFe_{12} , $a = b = 8.79 \text{ \AA}$ and $c = 12.14 \text{ \AA}$ for $\text{Nd}_2\text{Fe}_{14}\text{B}$, $a = 7.38$, $b = 4.56 \text{ \AA}$, and $c = 5.64 \text{ \AA}$ for FeB type SmCu, and $a = b = c = 2.84 \text{ \AA}$ for bcc Fe obtained by our calculations, respectively. Collinear spin structures neglecting the spin-orbit coupling of the valence electrons are considered with the energy cutoff of 500 Ry. The k -point grids of

$8 \times 8 \times 14$ for SmFe_{12} and $8 \times 8 \times 6$ for $\text{Nd}_2\text{Fe}_{14}\text{B}$ unit cell were adopted, respectively, where the k -point grids for surfaces and interfaces were scaled according to their lattice parameters. The initial spin configuration has the antiparallel structure between a rare-earth element and Fe.

First, we discuss the energetic stability of rare-earth-compound surfaces. The surfaces are represented as repeated slab models, and separated by 10 \AA as the vacuum gap. In the case of SmFe_{12} surfaces, the surface-energy density γ is evaluated by

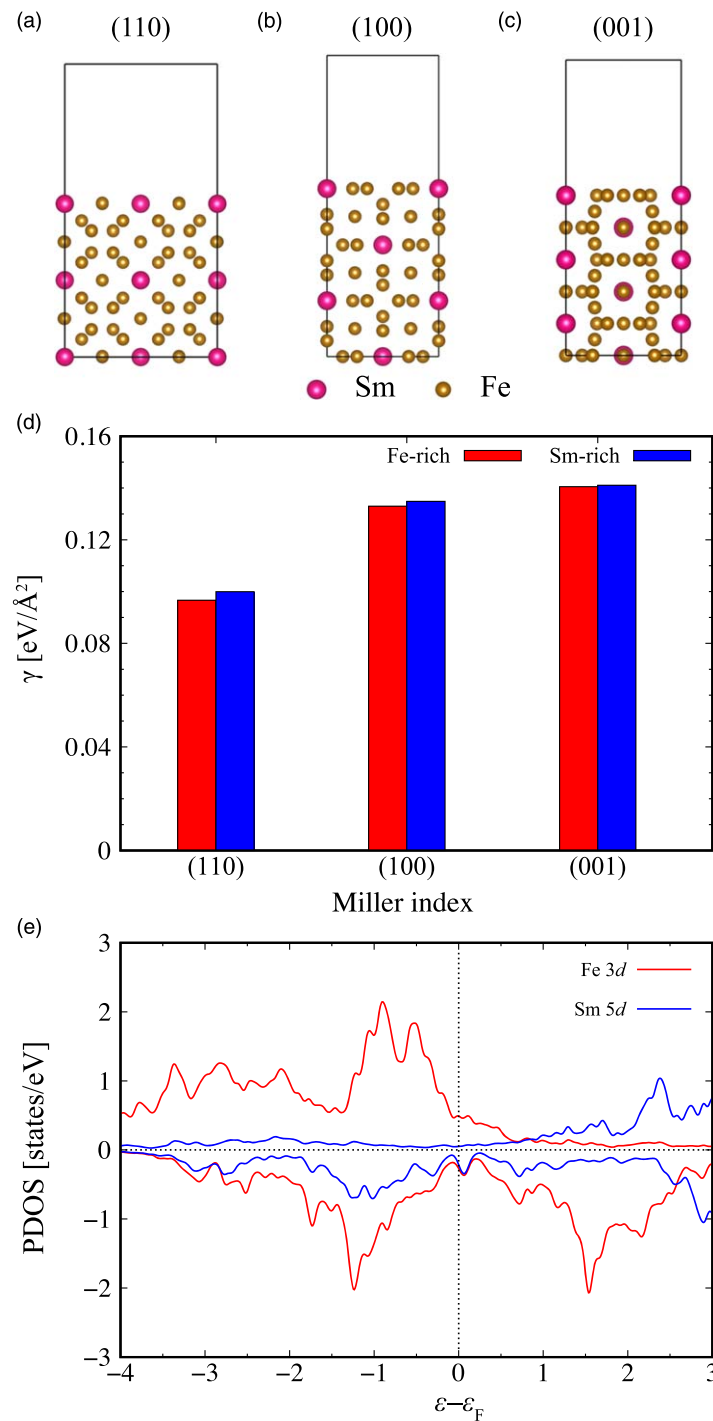


Fig. 1. (Color online) (a)–(c) Surface structures and (d) surface-energy densities γ of SmFe_{12} . (e) Projected density of states (PDOS) for $5d$ states of the Sm atoms and $3d$ states of the Fe atoms in the SmFe_{12} bulk. The upper (lower) panel denotes the PDOS of the majority (minority) spin, respectively. The single-electron energy is defined relative to the Fermi energy ϵ_F .

$$\gamma = \frac{E_{\text{slab}} - (N_{\text{Sm}}\mu_{\text{Sm}} + N_{\text{Fe}}\mu_{\text{Fe}})}{2A} \quad (1)$$

with the constraint of

$$E_{\text{SmFe}_{12}} = \mu_{\text{Sm}} + 12\mu_{\text{Fe}}, \quad (2)$$

where E_{slab} is the total energy of the surface slab, N_i is the number of atoms for the element i within the slab, μ_i is the chemical potential of the element i , A is the surface area, and $E_{\text{SmFe}_{12}}$ is the total energy of the SmFe_{12} bulk per formula unit. In the Fe-rich condition, we use $\mu_{\text{Fe}} = \mu_{\text{bcc-Fe}}$ meaning that SmFe_{12} is equilibrium with bcc Fe. In this case, μ_{Sm} is obtained by Eq. (2). Likewise, the Sm-rich condition is considered by $\mu_{\text{Sm}} = \mu_{\alpha\text{-Sm}}$ meaning that SmFe_{12} is equilibrium with $\alpha\text{-Sm}$.

The surfaces of SmFe_{12} with the Miller indices of (110), (100) and (001) are calculated for all possible 14 terminations, and we discuss only the most stable surface for each Miller index. As shown in Fig. 1, it is clear that the (110) surface is most stable. Furthermore, we have identified the trend that the most stable surface termination has the highest exposition of Sm atoms. This stabilization by the exposition of rare-earth atoms is attributed to the fact that the chemical bonding of $5d$ states of rare-earth atoms is weaker than that of Fe $3d$ states. The band energy of $5d$ states of rare-earth atoms which contribute to the chemical bonding is significantly smaller than that of $3d$ electrons of Fe atoms as depicted in Fig. 1(e) for the SmFe_{12} bulk. The Mulliken-population analysis revealed that the number of $5d$ electrons of the Sm atoms is approximately 1.4 while the number of $3d$ electrons of the Fe atoms is approximately 6.7 for the SmFe_{12} bulk.

Since we expect this trend is universal, we also examine another compound with a rare-earth element and a transition metal, $\text{Nd}_2\text{Fe}_{14}\text{B}$. In the case of $\text{Nd}_2\text{Fe}_{14}\text{B}$ surfaces, the surface-energy density γ is evaluated by

$$\gamma = \frac{E_{\text{slab}} - (N_{\text{Nd}}\mu_{\text{Nd}} + N_{\text{Fe}}\mu_{\text{Fe}} + N_{\text{B}}\mu_{\text{B}})}{2A}. \quad (3)$$

We adopt the condition rich in Nd and Fe and poor in B, where Nd is equilibrium with double hcp (dhcp) Nd as well

as Fe with bcc Fe: $\mu_{\text{Nd}} = \mu_{\text{dhcp-Nd}}$, $\mu_{\text{Fe}} = \mu_{\text{bcc-Fe}}$, and

$$\mu_{\text{B}} = E_{\text{Nd}_2\text{Fe}_{14}\text{B}} - (2\mu_{\text{dhcp-Nd}} + 14\mu_{\text{bcc-Fe}}), \quad (4)$$

where $E_{\text{Nd}_2\text{Fe}_{14}\text{B}}$ is the total energy of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ bulk per formula unit. By considering all possible 19 terminations, we also identified the most stable termination for the $\text{Nd}_2\text{Fe}_{14}\text{B}(100)$ surface. Also for this surface, the highest exposition of the rare-earth element, Nd, is seen as depicted in Fig. 2(a). Thus, the (001) and (110) surfaces of $\text{Nd}_2\text{Fe}_{14}\text{B}$ were examined for only the termination with the highest exposition of Nd atoms. As is clear from Fig. 2(b), the (001) surface is most stable for $\text{Nd}_2\text{Fe}_{14}\text{B}$, whereas the next stable surface index is (100).

Next, we discuss local magnetic properties of $\text{SmFe}_{12}(110)/\text{SmCu}(100)$ and $\text{SmFe}_{12}(110)/\text{Fe}(001)$ interfaces. In the case of the interface calculations, we relaxed the lattice parameters for the interface-perpendicular direction in addition to atomic coordinates. For the $\text{SmFe}_{12}(110)/\text{SmCu}(100)$ interface, $\sqrt{2} \times \sqrt{2} \times 1$ SmFe_{12} and $1 \times 1 \times 2$ SmCu were adopted, where the lattice mismatch is approximately 6.4% for the x -axis and 3.3% for the y -axis, respectively. For the $\text{SmFe}_{12}(110)/\text{Fe}(100)$ interface, $\sqrt{2} \times \sqrt{2} \times 3$ SmFe_{12} and $4 \times 5 \times 2$ Fe were adopted, where the lattice mismatch is approximately 5.4% for the x -axis and 0.7% for the y -axis, respectively. Our interface calculations contain up to approximately 550 atoms in the supercell. We evaluate the effective exchange-coupling constant J_{ex} by

$$J_{\text{ex}} = \frac{E_{\text{tot}}^{\text{APMA}} - E_{\text{tot}}^{\text{PMA}}}{2A}, \quad (5)$$

where $E_{\text{tot}}^{\text{APMA}}$ and $E_{\text{tot}}^{\text{PMA}}$ are the total energy of the optimized interface structures with the antiparallel magnetization alignment (APMA) and the parallel magnetization alignment (PMA) between SmFe_{12} grains, respectively. The total energy $E_{\text{tot}}^{\text{APMA}}$ can be calculated by a supercell doubled in the interface-perpendicular direction as depicted in Fig. 3.

Magnetic moments of the main-phase Fe atoms of each interface and the bulk are shown in Fig. 4(a). In the case of $\text{SmFe}_{12}(110)/\text{SmCu}(110)$ interface, the magnetic moments of

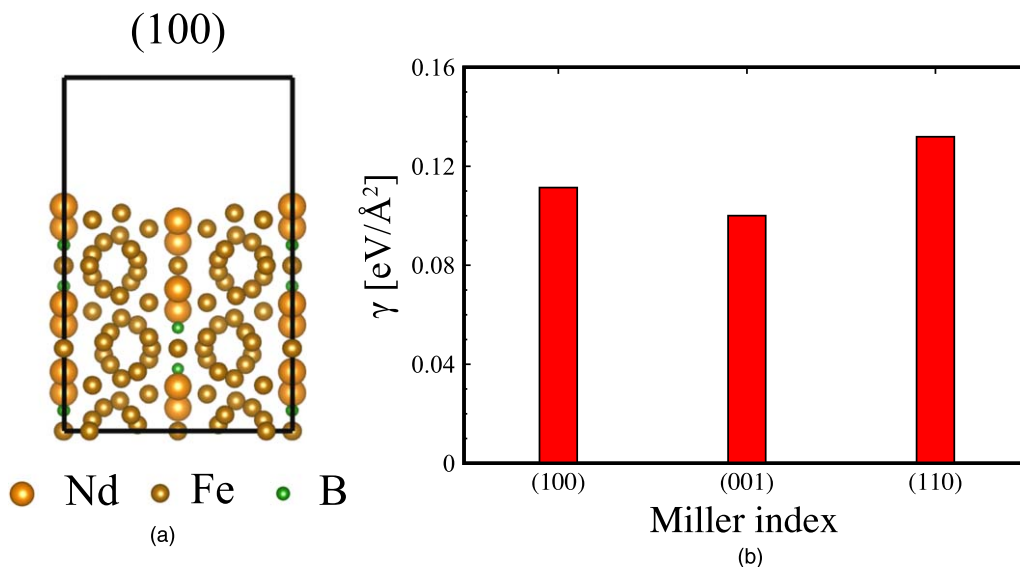


Fig. 2. (Color online) (a) Structure of the (100) surface and (b) surface-energy densities γ of $\text{Nd}_2\text{Fe}_{14}\text{B}$.

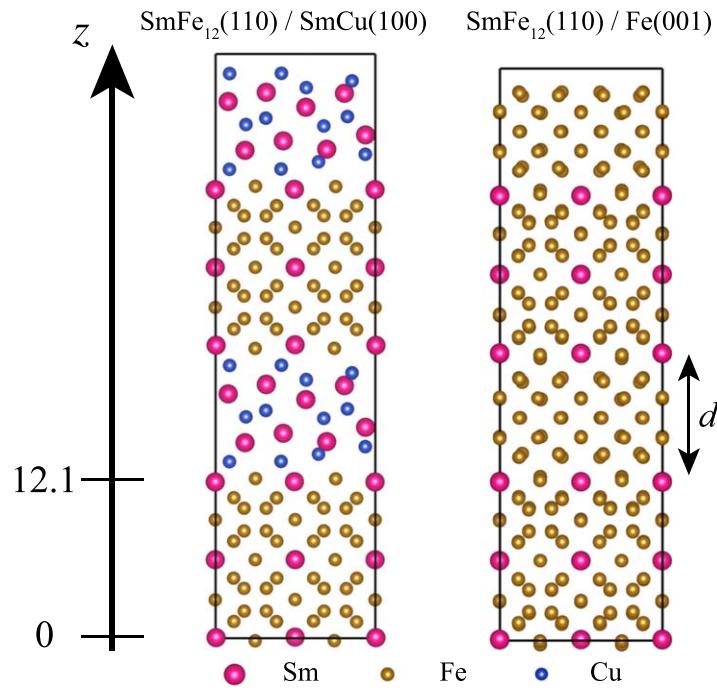


Fig. 3. (Color online) Optimized interface structures. The position with $z = 0$ and 12.1 represents the first interface layer of SmFe_{12} . d is the distance between SmFe_{12} grains defined by the first interface layers.

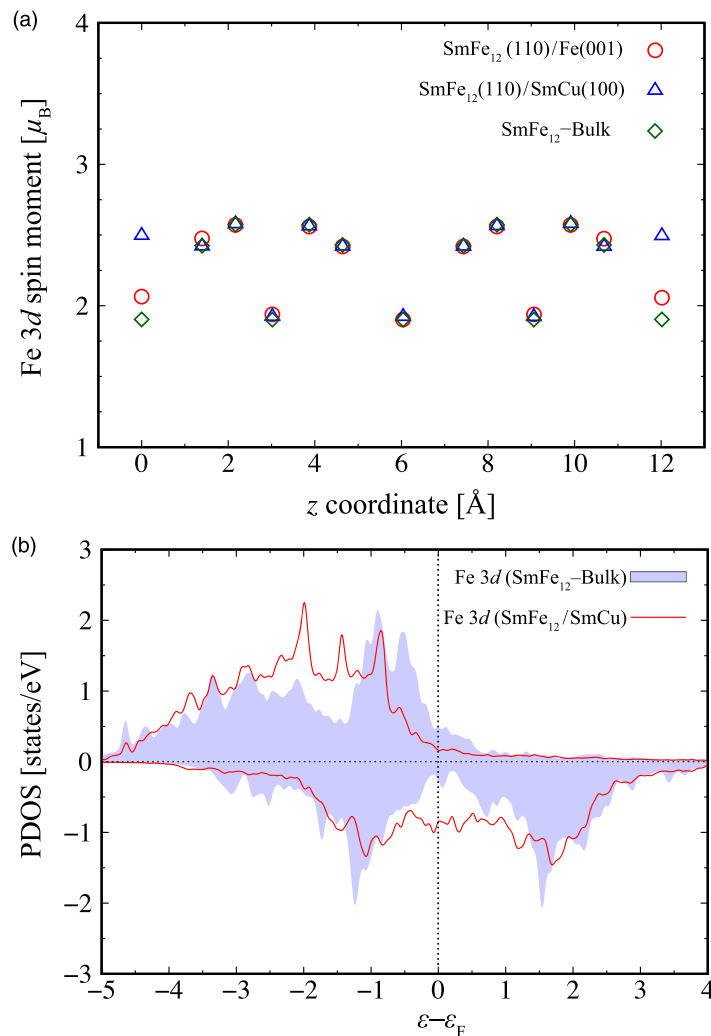


Fig. 4. (Color online) (a) Magnetic moments of the main-phase Fe atoms of each interface and the bulk averaged in the interface-parallel directions (x and y) as a function of the z coordinate. The position with $z = 0$ and 12.1 \AA corresponds the first interface layer. (b) The PDOS for $3d$ states of the main-phase Fe atoms located at the interface for the $\text{SmFe}_{12}/\text{SmCu}$ interface together with that of the SmFe_{12} bulk. The upper (lower) panel denotes the PDOS of the majority (minority) spin, respectively. The single-electron energy is defined relative to the Fermi energy ϵ_F .

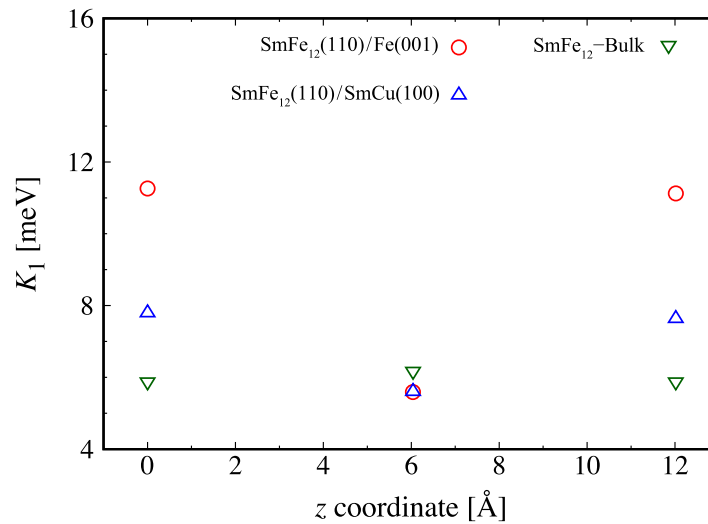


Fig. 5. (Color online) The magnetocrystalline anisotropy constant K_1 of the main-phase Sm atoms of each interface and the SmFe_{12} bulk averaged in the interface-parallel directions (x and y) as a function of the z coordinate. It should be noted that the quantization axis is set as the [001] direction of SmFe_{12} , not the direction perpendicular to the interface denoted as z . The position with $z = 0$ and 12.1 \AA corresponds the first interface layer.

Table I. Effective exchange-coupling constant J_{ex} and the distance between SmFe_{12} grains d .

Interface	J_{ex} [J m^{-2}]	d [\AA]
$\text{SmFe}_{12}(110)/\text{SmCu}(100)$	0.083	10.29
$\text{SmFe}_{12}(110)/\text{Fe}(001)$	0.983	9.51

the Fe atoms at the first interface layer ($z = 0$ and $z = 12.1 \text{ \AA}$) greatly increase compared with that of the SmFe_{12} bulk. This enhancement comes from a decrease in the hybridization between $3d$ minority-spin states of the main-phase Fe atoms, which is seen as weakened splitting between bonding and antibonding states in Fig. 4(b). To keep the charge neutrality, the majority spin increases by the amount of the decrease in the minority spin. In addition, the effective exchange-coupling constant J_{ex} is listed in Table I. It is clear that SmCu well suppresses the magnetic interaction between the main-phase grains compared with bcc Fe.

The magnetocrystalline anisotropy constant K_1 of the main-phase Sm atoms is evaluated up to the first order by

$$K_1 = -3J \left(J - \frac{1}{2} \right) \alpha_J A_2^0 \langle r^2 \rangle, \quad (6)$$

where J , α_J , $\langle r^2 \rangle$, and A_2^0 are the total angular momentum quantum number, the first Stevens factor, the spatial extent of the $4f$ orbitals, and the second-order crystal field coefficient,^{25,26} respectively. For Sm^{3+} , $J = 5/2$ ($L = 5$, $S = 5/2$) and $\alpha_J = 13/315$ were adopted. Electronic states of a specific crystal structure determine $A_2^0 \langle r^2 \rangle$ through the expanded radial component of the single-particle effective potential for the spherical harmonics Y_2^0 . In evaluating K_1 , the quantization axis is set as the [001] direction of SmFe_{12} , not the direction perpendicular to the interface denoted as z . As shown in Fig. 5, the stable magnetic direction is always [001] of the main phase ($K_1 > 0$) that is parallel to the (110) interface. The uniaxial anisotropy enhances at the interfaces compared with that of the bulk.

In summary, the most stable surface of SmFe_{12} was determined to be the (110) surface with the highest exposition of Sm atoms from first principles. This trend of the highest

exposition of rare-earth atoms, which comes from weaker chemical bonding of rare-earth $5d$ states compared with that of Fe $3d$ states, was universally observed for $\text{Nd}_2\text{Fe}_{14}\text{B}$ surfaces as well. Moreover, analyzing the magnetic properties of SmFe_{12} -based interfaces, we conclude that SmCu is preferred as a subphase of the SmFe_{12} -based permanent magnets. Our new findings in this paper will hopefully promote further development of new permanent magnets.

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