Doping Control of Magnetic Anisotropy for Stable Antiskyrmion Formation in Schreibersite (Fe,Ni)$_3$P with $S_4$ symmetry

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Magnetic skyrmions, vortex-like topological spin textures, have attracted much interest in a wide range of research fields from fundamental physics to spintronics applications. Recently, growing attention is also paid to antiskyrmions emerging with opposite topological charge in non-centrosymmetric magnets with $D_{2d}$ or $S_4$ symmetry. In these magnets, complex interplay among anisotropic Dzyaloshinskii–Moriya interaction, uniaxial magnetic anisotropy, and magnetic dipolar interactions generates various magnetic textures. However, the precise role of these magnetic interactions in stabilizing antiskyrmions remains to be elucidated. In this work, the uniaxial magnetic anisotropy of schreibersite (Fe,Ni)$_3$P with $S_4$ symmetry is controlled by doping and its impact on the stability of antiskyrmions is investigated. The authors’ magnetometry study, supported by ferromagnetic resonance spectroscopy, shows that the variation of the Ni content and slight doping with 4d transition metals considerably change the magnetic anisotropy. In particular, doping with Pd induces easy-axis anisotropy, giving rise to formation of antiskyrmions, while a temperature-induced spin reorientation is observed in an Rh-doped compound. In combination with Lorentz transmission electron microscopy and micromagnetic simulations, the stability of antiskyrmion as functions of uniaxial anisotropy and demagnetization energy is quantitatively analyzed, and demonstrated that subtle balance between them is necessary to stabilize the antiskyrmions.

1. Introduction

Vortex-like spin swirling objects, termed magnetic skyrmions and characterized by an integer topological winding number $N_{sk}$, have been extensively studied in the last decade, both in the fields of fundamental science and applications to spintronics devices.[1,2] One of the well-known mechanisms of skyrmion formation is the competition between ferromagnetic exchange interaction and the Dzyaloshinskii–Moriya interaction (DMI) arising from the lack of inversion symmetry. Skyrmions with helical (Bloch type) and cycloidal (Néel type) spin configurations have been observed in non-centrosymmetric magnets with chiral ($T$ or $O$ class) and polar ($C_n$ class) structures, respectively.[3–9] Recently, a new topological spin texture, the antiskyrmion, with opposite sign of $N_{sk}$ for the same polarity has attracted much attention. The antiskyrmion consists of both Bloch and Néel walls with the opposite helicities along two orthogonal axes, and its formation is attributed to the anisotropic DMI present in non-centrosymmetric tetragonal crystals belonging to the $D_{2d}$ or $S_4$ symmetry group both containing four-fold rotoinversion ($4$).\[10,11\] In real materials, antiskyrmions were first found in Heusler compounds with $D_{2d}$ symmetry, Mn$_{1.4}$PtSn and Mn$_{1.4}$P$_{0.9}$Pd$_{0.1}$Sn.$[12,13]$ More recently, the formation of antiskyrmions was also found in Fe$_{1.9}$Ni$_{0.9}$Pd$_{0.2}$P [Pd-doped (Fe,Ni)$_3$P] with $S_4$ symmetry$[14]$ and Fe/Gd-based multilayers.$[15]$ Lorentz transmission electron microscopy (ITEM) observation for thin plates of these
$D_{2d}$ and $S_2$ magnets shows that the antiskyrmions are square shaped, and transform into bullet-shaped non-topological bubbles and elliptically deformed Bloch skyrmions, depending on magnetic fields, temperature, and lamella thickness.\[3,13,14,16\] According to numerical simulations, magnetic dipolar interaction (demagnetization energy) plays a dominant role in the formation of square-shaped antiskyrmions.\[3,13,16,17\] Neél walls (Bloch lines) at the corners of an antiskyrmion tend to shrink so as to reduce the magnetic volume charge.\[16\] Magnetic force microscopy studies have shown that the size of antiskyrmions increases significantly as the crystal thickness is increased,\[14,19\] and anisotropic fractal-like domains with $\mathcal{F}$ symmetry are induced near the surface of bulk crystals\[14,20\] by the interplay between DMI, uniaxial magnetic anisotropy, and dipolar interactions to reduce the magnetic charge on the surface.\[21\]

Despite these findings in the two families of antiskyrmion-hosting magnets, the relation between the stability of antiskyrmions and magnetic interactions (DMI, magnetic anisotropy, and dipolar interaction) is still unclear due to the lack of experimental studies where the relative strength of magnetic interactions is tuned systematically. In this work, we succeeded in controlling the magnetic anisotropy of schreibersite (Fe,Ni)$_3$P with $S_2$ symmetry by chemical doping to observe the formation of stable antiskyrmions. First, we searched for the appropriate solid solution of Fe and Ni to reduce the easy-plane anisotropy. Next, using 4d transition metals with strong spin-orbit coupling, we further modified the magnetic anisotropy to easy-axis type, leading to the formation of stable antiskyrmions and skyrmions. We finally identified the stable region of antiskyrmions and skyrmions on the plane of uniaxial magnetic anisotropy and demagnetization energy, thereby demonstrating the subtle balance between them to give rise to the antiskyrmion spin texture.

### Table 1. Lattice constants ($a, c$) at room temperature, magnetic transition temperature ($T_c$), saturation magnetization ($M_s$), and uniaxial anisotropy constant ($K_u$) at 300 and 2 K for (Fe,Ni)$_3$P and doped with 4d transition metals.

<table>
<thead>
<tr>
<th>Composition</th>
<th>$a$ [Å]</th>
<th>$c$ [Å]</th>
<th>$T_c$ [K]</th>
<th>$M_s$ (300 K) [kA m$^{-1}$]</th>
<th>$M_s$ (2 K) [kA m$^{-1}$]</th>
<th>$K_u$ (300 K) [kJ m$^{-3}$]</th>
<th>$K_u$ (2 K) [kJ m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_3$P</td>
<td>9.1018(8)</td>
<td>4.4587(4)</td>
<td>681</td>
<td>1080</td>
<td>1160</td>
<td>$-647$</td>
<td>$-848$</td>
</tr>
<tr>
<td>(Fe$<em>{0.82}$Ni$</em>{0.18}$)$_3$P</td>
<td>9.0713(4)</td>
<td>4.4627(2)</td>
<td>557</td>
<td>801</td>
<td>925</td>
<td>$-98.4$</td>
<td>$-205$</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0425(5)</td>
<td>4.4607(3)</td>
<td>472</td>
<td>518</td>
<td>743</td>
<td>$-6.73$</td>
<td>$-38.8$</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0266(5)</td>
<td>4.4561(3)</td>
<td>334</td>
<td>306</td>
<td>632</td>
<td>$-4.06$</td>
<td>$-44.6$</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0006(5)</td>
<td>4.4429(3)</td>
<td>152</td>
<td>--</td>
<td>381</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0934(6)</td>
<td>4.4907(3)</td>
<td>337</td>
<td>363</td>
<td>693</td>
<td>$-5.65$</td>
<td>$-53.2$</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0931(7)</td>
<td>4.4855(4)</td>
<td>394</td>
<td>503</td>
<td>731</td>
<td>1.89</td>
<td>$-20.1$</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.0797(6)</td>
<td>4.4745(3)</td>
<td>399</td>
<td>511</td>
<td>750</td>
<td>22.2</td>
<td>51.3</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.1122(7)</td>
<td>4.4865(4)</td>
<td>398</td>
<td>474</td>
<td>707</td>
<td>27.9</td>
<td>83.8</td>
</tr>
<tr>
<td>(Fe$<em>{0.80}$Ni$</em>{0.20}$)$_3$P</td>
<td>9.1199(6)</td>
<td>4.4895(3)</td>
<td>392</td>
<td>451</td>
<td>704</td>
<td>33.5</td>
<td>114</td>
</tr>
</tbody>
</table>

2. Results and Discussions

2.1. Structural Properties

We synthesized bulk single crystals of schreibersite (Fe$_{1-x}$Ni$_x$)$_3$P ($0 \leq x \leq 0.66$) and those doped with small amounts of 4d transition metals (Ru, Rh, and Pd) listed in Table 1 by a self-flux method (see Note S1, Table S1, Supporting Information for details of sample preparation). Using powder X-ray diffraction, we confirmed that all the compounds crystallize in a non-centrosymmetric tetragonal structure with the space group of $I4$ (No. 82, $S_2^*$) as shown in Figure 1a (see Note S2, Figures S1,S2, Supporting Information for details). The tetragonal lattice constants ($a, c$) obtained by Rietveld analysis are plotted in Figure 1b. The parameter $a$ decreases linearly with increasing Ni concentration, while $c$ is almost unchanged below $x = 0.47$, in good agreement with a previous study.\[22\] When a small amount of Pd is substituted for Ni, both $a$ and $c$ increase linearly following Vegard’s law. Similar increase in the lattice constants is also observed with Ru and Rh doping.

2.2. Magnetometry

To characterize bulk magnetic properties, magnetization ($M$) was measured under magnetic fields applied parallel to the [110] and [001] axes, being perpendicular and parallel to the $\mathcal{F}$ axis, respectively. For the magnetization measurements, single crystals were cut into a rectangular shape (Figure S3, Supporting Information) so that the demagnetization factors in the [110] and [001] directions were the same. By adopting this sample shape with the same demagnetization factors, the uniaxial magnetic anisotropy constant ($K_u$) is directly obtained, without explicitly taking the demagnetization effect into account, from the difference between the Helmholtz magnetic free energy along the [110] and [001] axes.\[23\]

$$K_u = \int_0^{M_s} \left[ H_{[110]}(M) - H_{[001]}(M) \right] dM$$

where $M_s$ is the saturation magnetization, and $H_i(M)$ represents the magnetic field along the $i$-axis. Therefore, $K_u$ is equal to the area enclosed by the magnetization curves along the two directions. In the present case, the magnetization process along the easy axis is dominated by the displacement of domain walls, but the contribution of this process is excluded in Equation (I). The sign of $K_u$ indicates the direction of the anisotropy; $K_u > 0$ for the easy-axis anisotropy while $K_u < 0$ for the easy-plane type.

The temperature dependence $M(T)$ at 0.01 T and the magnetic field variation $M(H)$ at 2 K in (Fe$_{1-x}$Ni$_x$)$_3$P are presented.
in Figure 2. Fe$_3$P exhibits a ferromagnetic transition around 680 K and shows strong easy-plane anisotropy, as indicated by smaller $M$ values and larger saturation field in the [001] axis than those in the [110] axis (Figure 2a,f). Partial substitution of Fe with Ni lowers the magnetic transition temperature $T_c$ (Figure 2b–e) and decreases the saturation value of magnetization $M_s$ (Figure 2g–j). Furthermore, the difference between the magnetization curves along the [110] and [001] axes becomes smaller as the Ni substitution proceeds, and is the smallest at the Ni concentration of 37%. $M(T)$ of (Fe$_{0.34}$Ni$_{0.66}$)P decreases below 40 K (Figure 2e) probably due to the spin glass behavior of the diluted Fe moments.

The magnetic parameters, $T_c$, $M_s$, and $K_u$, obtained from the magnetization measurements using Equation (1) are plotted in Figure 2k–m as a function of Ni concentration $x$. The monotonic decrease in $T_c$ and $M_s$ with increasing $x$ is in accord with the previous report on polycrystalline samples. While there have been several studies on the magnetic properties of (Fe$_{1-x}$M$_x$)$_3$P (M: Cr, Mn, Co, and Ni) magnetocrystalline anisotropy has been reported only for (Fe$_{1-x}$Co$_x$)$_3$P. As shown in Figure 2m, the large negative value of $K_u$ for Fe$_3$P ($\sim 848$ kJ m$^{-3}$ at 2 K) determined in the present study coincides with the previous report. The absolute value of $K_u$ is rapidly suppressed by Ni substitution, reaching a minimum at $x = 0.37$ ($\sim 39$ kJ m$^{-3}$ at 2 K). Nevertheless, the easy-plane anisotropy ($K_u < 0$) persists throughout the whole Ni concentration range in the present study of (Fe$_{1-x}$Ni$_x$)$_3$P.

Having thus established that the strong in-plane magnetic anisotropy (negative $K_u$) in (Fe$_{1-x}$Ni$_x$)$_3$P can be appreciably reduced around $x = 0.4$ while keeping high $T_c$ above room temperature, next we aim to further control $K_u$ and to reverse its sign via doping with 4d transition metals. Figure 3 shows the effect of 4d transition-metal doping on the magnetic properties. In the Ru-doped compound, (Fe$_{0.59}$Ni$_{0.41}$)$_3$P$_{0.09}$P (Figure 3a,f), weak easy-plane anisotropy is observed in the whole temperature range below $T_c \approx 340$ K, as in the case of (Fe,Ni)$_3$P. On the other hand, the Rh-doped sample, (Fe$_{0.60}$Ni$_{0.40}$)P (Figure 2b,g), shows a complex temperature dependence. Below $T_c = 400$ K, the magnetization along the [110] axis increases gradually upon cooling, whereas that along the [001] axis is almost independent of temperature. The magnetization along the [110] axis saturates at 100 K, below which the magnetization along the [001] axis slightly decreases. This behavior is a typical indicator of spin reorientation from the c-axis to the ab-plane, which is often seen in uniaxial ferromagnets such as MnBi$_2$, Fe$_3$Sn$_2$, and Mn$_3$PtSn. The spin reorientation temperature in the Rh-doped compound is determined to be $T_{SR} \approx 100$ K where the kink-like anomaly is observed. For another dopant Pd, 4% doped (Fe$_{0.63}$Ni$_{0.37}$P)$_3$P (Figure 3b,g) does not show spin reorientation and exhibits weak easy-axis anisotropy in the whole temperature range below $T_c = 400$ K. In Pd 7% doped (Fe$_{0.61}$Ni$_{0.39}$P)$_3$P (Figure 3d,i) and 9% doped (Fe$_{0.62}$Ni$_{0.38}$P)$_3$P (Figure 3e,i), the easy-axis anisotropy is more clearly seen than in the Pd 4% doped sample.

The values of $T_c$ and $K_u$ in the investigated compounds are plotted against temperature in Figure 3k,l. While the $M_s$ values are similar for the different compositions, the sign and the absolute value of $K_u$ considerably change with the 4d metal dopant species. In particular, easy-axis anisotropy ($K_u < 0$) is induced by small amount of Pd doping, and the value of $K_u$ increases with decreasing temperature and increasing the Pd concentration. The temperature dependences of $K_u$ and $M_s$ in the Pd 7% and 9% doped compounds are found to obey the relation $K_u(T) \propto \left[M_s(T)^2\right]^{2.7}$ (Figure S4, Supporting Information). The power law with an exponent close to 3 agrees with the theoretical models for uniaxial anisotropy. For the Pd 7% compound that shows $M_s \approx 474$ kA m$^{-1}$ and $K_u = 28$ kJ m$^{-3}$ at room temperature, the quality factor is estimated to be $Q \approx 0.2$, where $Q$ is defined...
as $Q = K_u / (\mu_0 M_s^2 / 2)$, the ratio of the uniaxial anisotropy constant to the maximum of demagnetization energy. These $K_u$ and $Q$ values are small as compared with those of the industrially important commercial permanent magnets, such as (Sr,Ba)Fe$_2$O$_{19}$, Nd$_2$Fe$_{14}$B, SmCo$_5$, and the recently reported Heusler compound Mn$_{1.4}$PtSn ($K_u \approx 171$ kJ m$^{-3}$, $Q \approx 1.7$ at room temperature). The values of $K_u$ for the Rh-doped compound are in between those for the Ru- and Pd-doped ones, and change from very small positive values at room temperature to negative values at low temperatures, leading to the temperature-induced spin reorientation. The significant change in the magnetic anisotropy from easy-plane to easy-axis with the Pd doping indicates the importance of enhanced spin-orbit coupling in the 4d element. The systematic variation in the magnetic anisotropy with change in the dopants Ru, Rh, and Pd is probably dominated by band filling of 4d orbitals, or position of the Fermi level.

While the systematic change of $K_u$ with composition and temperature was identified by the magnetometry study using Equation (1), we performed ferromagnetic resonance (FMR) spectroscopy experiments on the Pd 7% compound to determine $K_u$ by another method, and thus further validate our magnetometry-based approach for the quantification of anisotropy.

### 2.3. Ferromagnetic Resonance Spectroscopy

We carried out FMR spectroscopy measurements at 9.4 GHz on a cylindrical disk prepared from a Pd 7% crystal and shown in the inset of Figure 4b. Figure 4a displays representative field-swept FMR spectra recorded at room temperature for various orientations of the magnetic field applied in the plane of the disk, which contains both the [110] and [001] axes. The maxima of the microwave absorption curves correspond to the FMR field, $H_{res}$, whose angular dependence is displayed in Figure 4b for a full rotation of the field in the plane of the disk. The minimum of $H_{res}$ is observed for magnetic field along the [001]...
axis, while the maximum is reached for field parallel to the [110] axis, clearly demonstrating the easy-axis nature of the anisotropy with the [001] direction being the easy axis. Due to the cylindrical shape of the sample, the demagnetization factor is unchanged upon the field rotation, hence the angular dependence of $H_{\text{res}}$ is solely governed by $K_u$. Similar $H_{\text{res}}(\theta)$ curves were recorded at 250, 350, and 380 K. The $K_u$ values obtained by fitting these curves, as described in the Experimental Section and in refs. [37–39], are plotted in Figure 3l. These values are in excellent agreement with those obtained from the analysis of the magnetization, supporting the fully quantitative determination of $K_u$ in the present work.

2.4. Magnetic Textures Observed by Lorentz Transmission Electron Microscopy

In order to observe magnetic structures in real space, LTEM measurements were carried out on (001) thin plates. We present the magnetic induction fields as deduced by transport-of-intensity equation (TIE) analyses for the compounds with Pd 7% ($t \approx 130$ nm), Pd 4% ($t \approx 140$ nm), and Rh 8% ($t \approx 180$ nm) in Figure 5. The stripe pattern with a few hundred nm periods observed for all the compounds at room temperature and zero magnetic field (Figure 5a,d,g) corresponds to anisotropic helices with opposite helicities propagating along the [110] and [\bar{1}10] axes. In the Pd 7% sample, square antiskyrmions appear uniformly over the plate under a magnetic field perpendicular to the specimen (Figure 5b). Note that high-density antiskyrmions are observed only after the sample plate is tilted under a magnetic field to initially create non-topological bubbles, and tilted back to the original perpendicular position as detailed in the caption for Figure 5.

In the Pd 4% sample, square antiskyrmions and elliptically deformed skyrmions coexist under a magnetic field (Figure 5e). This coexistence state is also observed for $t = 170$, 190, and...
220 nm, but a homogeneous antiskyrmion lattice is not formed. At the thickness of $t \approx 80$ nm, only elliptic skyrmions are observed. The (co)existence of skyrmions in spite of the anisotropic DMI indicates that the dipolar interaction is dominant over the DMI in this system.

In the Rh 8% sample, while dense elliptic skyrmions with mixed helicities are stabilized under a magnetic field (Figure 5h), no antiskyrmions are observed at any field for any sample thickness from 70 to 240 nm. As the temperature is lowered in zero field, the stripe pattern changes to large (approximately several micrometers) domains with in-plane magnetizations (Figure 5j), which is consistent with the behavior of spin reorientation in the bulk magnetization measurement (Figure 3b). The in-plane domains are arranged in such a way that the magnetic flux is closed as indicated with white arrows. The transition from the anisotropic helices to the in-plane closure domains starts at higher temperatures for smaller thickness, for example, 200 K for $t = 70$ nm, 143 K for $t = 110$ and 150 nm, and 130 K for $t = 180$ nm. Furthermore, this transformation is accompanied by a coexistence region and a large thermal hysteresis; the stripe patterns remain partially at low temperatures, but once the change into the in-plane domains is complete, they hardly recover in a subsequent heating process (Figure S5, Supporting Information).

In Figure 5f,i, enlarged views of an elliptic skyrmion are presented. The elliptic deformation is due to the cooperative interplay between the dipolar interaction and the anisotropic DMI inherent to the crystal structure with $D_{2d}$ or $S_4$ symmetry,[13,14,16] and hence distinct from elliptic skyrmions induced by artificial anisotropy.[40,41] From the observed ellipticity, the magnitude of DMI is roughly estimated to be $\approx$26% of the demagnetization energy.[13] In addition, the variation of the DMI with composition is negligible since the ellipticity of the skyrmion is comparable for the Pd 4% and Rh 8% compounds. Although the change in the DMI for these compounds investigated in this work is small, it might vary significantly in a wider compositional range, similarly to the Co/Pt bilayers where the interfacial DMI depends on the band filling of 5d orbitals.[42] To determine the anisotropic DMI more quantitatively and understand its compositional dependence comprehensively, further studies (e.g., Brillouin light scattering,[43] spin-wave spectroscopy[44]) are necessary. Therefore, while the anisotropic DMI in this system is indeed important, we focus hereafter on the effects of larger and composition/temperature-dependent demagnetization energy and magnetic anisotropy on the formation of the topological spin textures.

2.5. Stability of Antiskyrmions Governed by Demagnetization Energy and Uniaxial Anisotropy

To understand the effect of the thickness-dependent dipolar interactions quantitatively, we estimate demagnetization energy $E_d$ for the thin plates using the following theoretical equation for a helical stripe (Bloch wall type) with a period of $\lambda$ and a film thickness of $t$:[19,45]

$$E_d = \frac{\mu_0 M_s^2}{2} \int \frac{2\pi t}{\lambda}$$

(Figure 4). Ferromagnetic resonance (FMR) spectroscopy on (Fe$_{0.63}$Ni$_{0.30}$Pd$_{0.07}$)$_3$P at 300 K. a) FMR spectra, representing the absorbed power $P_{abs}$ as a function of the magnetic field strength, $\mu_0 H$, at a constant microwave frequency 9.4 GHz, displayed at selected $\theta$ angles of the magnetic field. The vertical bars, marking the resonance field positions, are guides to the eyes for tracing the angular periodicity of the spectra. b) Dependence of the resonance field at room temperature on the orientation of the magnetic field, $H_{res}(\theta)$, upon its rotation in the plane spanned by the [001] and [110] axes. The angle $\theta$ is measured from the [001] axis as indicated in the inset, which depicts the single crystal under investigation prepared as a thin cylindrical disk. The solid black line shows a fit by uniaxial magnetocrystalline anisotropy[37–39] as described in the text.
Figure 5. Magnetic structures observed by LTEM. a–j) Color mapping of in-plane magnetic induction fields deduced by transport-of-intensity equation (TIE) analyses of over- and under-focus LTEM images.\(^{[86]}\) The color-coded wheel and the schematic figure of the experimental configuration (crystal axes of the thin plate and the external field) at the bottom right side are common for all the panels. The images of antiskyrmions and skyrmions (panels (b,c,e,h)) were obtained after tilting the plate under the external field and then back to the original position, as described in the following, where the tilt angles around the [T10] and [T10] axes are denoted as \(\alpha\) and \(\beta\), respectively. Field images for (Fe\(_{0.63}\)Ni\(_{0.30}\)Pd\(_{0.07}\))\(_3\)P with thickness \(t = 130\) nm at (a) 295 K and 0 mT, (b) 295 K and 350 mT [process: 0 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 350 mT \((\alpha = 12^\circ)\) \(\rightarrow\) 350 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 650 mT \((\alpha = 0^\circ)\)], and (c) 100 K and 650 mT [process: ZFC \(\rightarrow\) 100 K and 0 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 550 mT \((\alpha = 12^\circ)\) \(\rightarrow\) 550 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 650 mT \((\alpha = 0^\circ)\)]. Field images for (Fe\(_{0.63}\)Ni\(_{0.30}\)Pd\(_{0.07}\))\(_3\)P with \(t = 140\) nm at (d) 295 K and 0 mT, and (e,f) 295 K and 385 mT [process: 0 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 385 mT \((\alpha = 2.4^\circ)\) \(\rightarrow\) 385 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 450 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 450 mT \((\alpha = 0^\circ)\)]. Field images for (Fe\(_{0.60}\)Ni\(_{0.32}\)Rh\(_{0.08}\))\(_3\)P with \(t = 180\) nm at (g) 295 K and 0 mT, (h,i) 295 K and 450 mT [process: 0 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 450 mT \((\alpha = 0^\circ)\) \(\rightarrow\) 450 mT \((\alpha = 5^\circ)\) \(\rightarrow\) 450 mT \((\alpha = 0^\circ)\)], and (j) 94 K and 0 mT. Panels (f) and (i) display enlarged views of the elliptic skyrmions shown in panels (e) and (h), respectively. The ellipticity (ratio of the length of the major axis to that of the minor axis) of the skyrmion in panels (f) and (i) are 1.70 and 1.73, respectively. The magnetic induction fields in the in-plane domains (panel (j)) are also indicated with white arrows.

where the function \(f(x)\) is defined as \(f(x) = (1 - e^{-x})/x\). For small \(x\) (i.e., \(t \ll \lambda\)), \(f(x)\) is simplified as \(f(x) \approx 1 - x/2\), while \(f(x) = 1/x\) for large \(x\) (i.e., \(t \gg \lambda\)). Figure 6a shows \(\lambda(t)\) of the anisotropic helices at room temperature and zero field for the composition with Pd 7%, Pd 4%, and Rh 8%. The thickness dependence is well described by the Kittel’s law \(\lambda(t) \approx t^{1/2}\),\(^{[86]}\) which is attributed to the competition between demagnetization energy and domain wall energy. The calculated \(E_d\) by using Equation (2) at room temperature for each compound is plotted against \(t\) in Figure 6b, which increases monotonically with decreasing thickness.

Finally, we map out the magnetic objects observed by LTEM onto the plane of \(K_s\) and \(E_d\) in Figure 6c. Here, anisotropic helices and in-plane domains at zero field, and antiskyrmions/skyrmions under magnetic fields are plotted all together. The \(K_s-E_d\) phase diagram indicates that antiskyrmions are stabilized when \(K_s\) is positive, sufficiently large and comparable to \(E_d\). On the other hand, when \(K_s\) is very small as compared to \(E_d\), as in the cases of Rh doping, or Pd doping with small thickness, elliptic skyrmions become more dominant. This result proves that the strong dipolar interaction destabilizes the antiskyrmions with magnetic volume charge, and favors the Bloch skyrmions without it. Therefore, uniaxial anisotropy and dipolar interaction are both important ingredients for stabilizing antiskyrmions in \(S_1\) magnets with anisotropic DMI (and probably \(D_{2z}\) magnets as well). The significant role of uniaxial anisotropy and dipolar interaction for stabilizing antiskyrmions has been also demonstrated in multilayers.\(^{[10]}\)

The phase diagram in Figure 6c also describes the temperature-induced change from the anisotropic helices to the in-plane domains when the sign of \(K_s\) changes to negative in the case of the Rh 8% doping (although initially formed anisotropic helices at room temperature with \(K_s > 0\) can survive to the region of \(K_s < 0\) as a metastable state). The phase boundary between the helices and the in-plane domains shows a positive slope, indicating that the dipolar interaction also contributes to the spin reorientation.
The easy-plane anisotropy may also give rise to more interesting in-plane topological magnetism such as bimeron.\[47,48\]

2.6. Micromagnetic Simulations

The experimental observation of the antiskyrmions stabilized by uniaxial anisotropy is in qualitative agreement with our micromagnetic simulations, presented in Figure 7. In Figure 7a, we show simulation results of magnetic textures at various \(K_u\) and external magnetic fields with a constant dipolar energy density of \(E_d=66\ \text{kJ m}^{-3}\) (note that the horizontal axis is different from that in Figure 6c). We start from an initially triangular antiskyrmion lattice and relax it at finite temperature. As a result, we obtain a field-polarized ferromagnetic state at large magnetic fields \(\mu_0 H \geq 500\ \text{mT}\), in-plane states at low anisotropy \(K_u \leq 30\ \text{kJ m}^{-3}\), and antiskyrmions and skyrmions under fields, for the Pd 7%, Pd 4%, and Rh 8% compounds with various thicknesses shown in panel (b). Low-temperature data for Pd 7% (\(t=130\ \text{nm}\)) and Rh 8% (\(t \leq 190\ \text{nm}\)) are also included. The data points for Pd 7% are reproduced in part from our earlier work.\[14]\ (Copyright 2021, Springer Nature).

3. Conclusion

We have systematically studied the magnetic properties of schreibersite \((\text{Fe},\text{Ni})_3\text{P}\) with \(S_4\) symmetry by performing magnetometry, FMR spectroscopy, LTEM, and micromagnetic simulations, demonstrating that the magnetic anisotropy can be finely controlled by the composition to stabilize antiskyrmions. The strong easy-plane anisotropy of Fe\(_3\)P is rapidly suppressed by partial Ni substitution, and when additionally doped with a small amount of Pd, the magnetic anisotropy switches to an easy-axis type, leading to the formation of antiskyrmions. The Rh-doped compound exhibits a temperature-induced spin reorientation transition, which is directly observed by LTEM. The phase diagram regarding the magnetic textures clearly shows stable regions of antiskyrmions and elliptic skyrmions on the plane of the uniaxial anisotropy and the demagnetization energy. These findings unveil that easy-axis type uniaxial magnetic anisotropy and dipolar interaction with appropriate balance are both necessary to stabilize antiskyrmions, and will help to design new antiskyrmion systems toward applications in spintronics.

4. Experimental Section

Sample Preparation: Bulk single crystals of \(M_3\text{P}\) (\(M:\) Fe, Ni, Ru, Rh, and Pd) were synthesized by a self-flux method from the initial molar ratio...
Temperature stability of about 1 K. The measurements were performed on a cylindrical thin disk (diameter/thickness ≈ 5), whose plane contains both the tetragonal [001] axis and the [110] axis perpendicular to it. The ° in 5 cylindrical disk at selected temperatures: 250, 300, 350, and 380 K. To obtain the uniaxial anisotropy parameter 
transmission electron microscope (JEM-2100F, JEOL) equipped with a double-tilt liquid-nitrogen holder (Gatan 636) and a double-tilt heating holder (Protochips: Fusion select). External magnetic fields applied to the (001) plates were obtained by tuning the objective lens current to the (001) plates were obtained by tuning the objective lens current

Figure 7. Thickness-averaged magnetization as obtained from 3D micromagnetic simulations for a 100 nm thick film. a) Simulated magnetic textures on the plane of uniaxial anisotropy energy \( K_u \) and external magnetic field \( \mu_0 H \). The color encodes the orientation of the magnetization with white (black) indicating the +z (−z) component. The color of the frame of every panel encodes the total skyrmion number from +4 (blue, four skyrmions) to −4 (red, four antiskyrmions). The dipolar energy density in the simulations is \( E_d = 66 \text{ kJ m}^{-3} \). Enlarged views of the magnetic textures at \( \mu_0 H = 300 \text{ mT} \) and b) \( K_u = 140 \), c) 80, and d) 40 \text{ kJ m}^{-3} \), where the skyrmion number for each magnetic object is also indicated (+1 for skyrmion, −1 for antiskyrmion).

Magnetization Measurements: For magnetization measurements, single crystals were cut into a 1-mm-scale rectangle with flat (110) and (001) axes (Figure S3, Supporting Information). Magnetization measurements were carried out using a superconducting quantum interference device magnetometer (MPMS3, Quantum Design) equipped with an oven option.

FMR Measurement: Angular dependent FMR experiments were performed for the temperature range 250 K ≤ \( T \) ≤ 380 K, using a Bruker ELEXSYS E500 CW X-band (9.4 GHz) spectrometer. The sample of \( \text{Fe}_{0.63}\text{Ni}_{0.37}\text{Pd}_{0.67} \) was in a continuous nitrogen gas-flow cryostat with temperature stability of about 1 K. The measurements were performed on a cylindrical thin disk (diameter/thickness = 5), whose plane contains both the tetragonal [001] axis and the [110] axis perpendicular to it. The orientation of the sample was controlled by a programmable goniometer in \( \pi \) steps during a full rotation of the magnetic field in the plane of the cylindrical disk at selected temperatures: 250, 300, 350, and 380 K. To obtain the uniaxial anisotropy parameter \( K_u \) at these temperatures, the angular dependence of the resonance field was fitted using the Smit–Suhl formula,[49] similarly to the procedure followed in ref. [38].

LTEM Measurement: For LTEM measurements, (001) thin plates with various thickness were thinned from bulk single crystals by a focused ion beam system (NB5000, Hitachi); \( t \approx 70, 110, 150, 180, \) and 240 nm for \( \text{Fe}_{0.63}\text{Ni}_{0.37}\text{Pd}_{0.67} \); \( t = 80, 140, 170, 190, \) and 220 nm for \( \text{Fe}_{0.63}\text{Ni}_{0.37}\text{Pd}_{0.67} \); \( t = 50, 70, 100, 130, 160, \) and 210 nm for \( \text{Fe}_{0.63}\text{Ni}_{0.37}\text{Pd}_{0.67} \). LTEM measurements were performed with a transmission electron microscope (JEM-2100F, JEOL) equipped with a double-tilt liquid-nitrogen holder (Catan 636) and a double-tilt heating holder (Protochips: Fusion select). External magnetic fields applied to the (001) plates were obtained by tuning the objective lens current of JEM-2100F, which were parallel to the incident electron beam. The distribution of in-plane magnetic induction fields was obtained by a TIE analysis using over- and under-focus LTEM images.[10]

Micromagnetic Simulations: For the theoretical description of the magnetization the same continuum model as in ref. [14] was considered, that is, including the magnetic stiffness \( A_{xx} \), \( S_z \)-symmetric DMI, uniaxial anisotropy \( K_u \), Zeeman field \( H \), and dipolar interactions due to the saturation magnetization \( M_s \). For the numerical implementation, the modified version of MuMaX3[51,52] was used in which the sign of the derivatives in the DMI-field was flipped in one spatial direction. Thus, the DMI favored right-handed helices in the horizontal direction and left-handed helices in the vertical direction. The micromagnetic parameters were chosen as \( A_{xx} = 8.1 \text{ pJ m}^{-3}, D = 0.2 \text{ mJ m}^{-2}, \) and \( M_s = 600 \text{ kA m}^{-1} \). For obtaining the results in Figure 7, a triangular lattice of antiskyrmions was first relaxed at zero temperature at some convenient values of the magnetic field and anisotropy. The simulated system with periodic boundary conditions in the \( xy \)-plane measured 800 nm \( \times \) 700 nm \( \times \) 100 nm, discretized on \( 128 \times 112 \times 32 \) lattice sites, and contained 4 antiskyrmions. In a second step, this texture was used as the starting point for simulations at finite temperature \( T \) (\( T = 600 \text{ K} \)) for a timespan \( t \) after which the textures appeared to be in quasi-equilibrium (\( t = 10 \text{ ns} \)). This method yielded an approximation for the energetically most favorable texture which otherwise was a complex high-dimensional optimization problem with many local minima. The resulting thickness-averaged magnetization is shown in Figure 7 together with the skyrmion number which was the 2D winding number[31] up to a sign. The dipolar energy density \( E_d = 66 \text{ kJ m}^{-3} \) was determined by deterministically finding the optimized helical wavelength at every value of the anisotropy which turned out to be qualitatively constant in the regime of interest.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Note: Equation (1) was corrected on March 17, 2022, following a typesetting error on initial publication in Early View.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.


