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Quantitative understanding of thermal stability of $\alpha''$-Fe$_{16}$N$_2$

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Thermal stability of $\alpha''$-Fe$_{16}$N$_2$, which attracts much interest because of its superior magnetic properties featuring a large magnetocrystalline anisotropy ($K_m \sim 1 \times 10^7$ erg/cm$^3$) and saturation magnetization ($M_s \sim 234$ emu/g), though unfortunately thermally unstable, has been quantitatively studied.

$\alpha''$-Fe$_{16}$N$_2$ is a meta-stable iron nitride with body-centered tetragonal (bct) structure, which is essentially $\alpha$-Fe containing the nitrogen atoms ordered on interstitial sites. This material has attracted much interest since the first report of a ‘giant’ magnetic moment in it. Although the formation of this phase was already reported in 1951,2 it has been difficult to obtain monophasic samples in a large size of 10 g/batch and the decomposition mechanism remains the same. All the experimental data fall into a single curve, which may be expressed $\alpha$-Fe$_2$O$_3 \rightarrow \alpha$-Fe $\rightarrow \alpha''$-Fe$_{16}$N$_2$.5 In the starting powder no crystalline impurity phases such as $\gamma'$-Fe$_2$N, $\varepsilon$-Fe$_2$N, $\alpha$-Fe and iron oxides were detected by XRD (see Figure S1 in the Electronic Supplementary Information (ESI)). However, the presence of ca. 9 % of an amorphous phase, which was supposed to be insufficiently nitrided and consequently amorphized particles, $\alpha$-FeN$_x$ ($x < 0.125$), was suggested by the Rietveld analysis of the XRD result (see Figure S2(a) in the ESI). The average crystallite size of $\alpha''$-Fe$_{16}$N$_2$ NPs estimated by using the Scherrer formula was 29.6 nm. For the decomposition studies, the $\alpha''$-Fe$_{16}$N$_2$ NPs were sealed in borosilicate capillaries under N$_2$ or Ar and immersed in preheated oil baths (473, 493, 503 and 513 K) for certain periods of time ($t$). Temperature- and time-dependent XRD patterns taken under N$_2$ are shown in Figure S3 in ESI. Upon increment of the heating time ($t$), $\alpha''$-Fe$_{16}$N$_2$ decreases while $\alpha$-Fe and $\gamma'$-Fe$_2$N appear and increase. No other crystalline phases were detected, while the intensity of the broad peak assigned to an amorphous phase was doubled in an early stage but was soon decreased to the initial level, suggesting the presence of interfacial regions containing disordered nitrogen atoms.

In order to quantitatively estimate decomposition kinetics, the relative weight fractions of $\alpha''$-Fe$_{16}$N$_2$, $\alpha$-Fe, $\gamma'$-Fe$_2$N and the amorphous phase were estimated by using the Rietveld analyses (also see Figure S4 and Table S1 in the ESI). The fraction of decomposition, $D$, can be expressed as:

$$D = 1 - \frac{w_{Fe16N2}(T, t)}{w_{Fe16N2}(300, 0)}$$  \hspace{1cm} (1)

where $w_{Fe16N2}(300, 0)$ and $w_{Fe16N2}(T, t)$ represent the fraction of $\alpha''$-Fe$_{16}$N$_2$ before ($= 0.9056$) and after a heat-treatment at $T$ [K] for a certain period of time ($t$), respectively. Fig. 1a ~ d show the time dependence of decomposition at various temperatures. These are all well represented by the first order reaction model formulated as:

$$D = 1 - \exp(-k_{app}t)$$  \hspace{1cm} (2)

where $k_{app}$ is an apparent rate constant.14 Summarized in Fig. 1e are the $D$ vs. $t_{1/2}$ relation measured at different temperatures and atmospheres, where $t_{1/2}$ is the time when $D$ reaches 0.5 (see Table S2 in the ESI). All the experimental data fall into a single curve, revealing that the decomposition mechanism remains the same.
irrespective of temperature and atmosphere. Furthermore, it is worth noting that even the raw experimental data collected under \( N_2 \) and Ar fall into the same \( D \) vs. \( t \) curve, revealing that not only the basic mechanism but also the kinetic parameters are quantitatively the same for these atmospheres (see Figure S5 and S6 in the ESI).

Thermal decomposition is a thermally activated process, and \( k_{app} \) can be expressed as below using an Arrhenius-type equation:

\[
k_{app} = k_0 \exp(-\Delta E_{app}/RT)
\]

where \( k_0 \), \( \Delta E_{app} \), \( R \), and \( T \) are the frequency factor, apparent activation energy, gas constant and absolute temperature, respectively. From the so-called Arrhenius plot of \( \ln(k_{app}) \) vs. \( 1/T \) shown in Fig. 1f, \( k_0 \) and \( \Delta E_{app} \) have been deduced to be \( 1.98 \times 10^9 \) [1/h] and \( 199 \) [kJ/mol], respectively. Two previous works done on \( \alpha''-\text{Fe}_4\text{N} \) precipitates embedded in bulk Fe-N alloy matrices reported largely different values.\(^{12}\) Predicting the thermal stability of \( \alpha''-\text{Fe}_4\text{N} \) in an inert atmosphere quantitatively based on the present study, as shown in Fig. 2, \( \alpha''-\text{Fe}_4\text{N} \) devices should be kept below about 355 K in order to maintain their performance better than 99 % for 100 years, for instance. The time allowance vs. temperature relation shown in Figure S7 in the ESI must be quantitatively useful for development of device fabrication processes and others.

Fig. 3 shows plots of \( w_{\text{FeN}} \) vs. \( w_{\text{Fe}} \). All of the data points fall into the single line of \( w_{\text{FeN}} = 1.06 w_{\text{Fe}} \), revealing that \( \alpha''-\text{Fe}_4\text{N} \) thermally decomposes into a 4:1 molar mixture of \( \alpha'-\text{Fe} \) and \( \gamma'-\text{Fe}_2\text{N} \) without releasing nitrogen into the atmosphere. The increment of \( w_{\text{FeN}} \) and \( w_{\text{Fe}} \) ceases at about 0.45 due to the presence of the amorphous phase (\( w_{\text{amor}} \sim 0.1 \)). It is worth noting that, upon heat-treatment, the amorphous phase first increases to \( w_{\text{amor}} \sim 0.22 \) and subsequently decreases to the initial level of \( \sim 0.1 \) (see Figure S4(b) in the ESI). This behavior can be understood by assuming the existence of two amorphous phases: one is that already contained in the pristine sample which remains intact during heat-treatment (\( \sim 0.1 \)). The other arises from insufficient atomic rearrangements during thermal decomposition, which is responsible for the initial increment and the subsequent decrement.

Another important experimental fact is that evolution of nitrogen gas during decomposition was not detected at all by mass spectroscopic analyses done in an Ar stream (see Figure S8 in the ESI). Together with the XRD data, the thermal decomposition reaction can thus be exactly expressed as a solely intra-solid atomic rearrangement:

\[
\alpha''-\text{Fe}_4\text{N} \rightarrow 8(\alpha'-\text{Fe}) + 2(\gamma'-\text{Fe}_2\text{N})
\]

The observed \( \Delta E_{app} \) of 199 [kJ/mol] is closer to the activation energy for the diffusion of iron atoms in bcc-iron, 250 [kJ/mol],\(^{15}\) rather than to the activation energy for the diffusion of nitrogen atoms in Fe-N alloys, 90 [kJ/mol].\(^{16}\) Most probably the energy-consuming iron diffusion is the initial step of the reaction that is indispensably necessary to make space for nitrogen to be condensed to form \( \gamma'-\text{Fe}_2\text{N} \). To enhance the practical stability of \( \alpha''-\text{Fe}_4\text{N} \) it is necessary to suppress the formation of \( \gamma'-\text{Fe}_2\text{N} \). Doping of Ti, Cr, Al and Mn (3-15 %, nominal), known to suppress the formation of \( \gamma'-\text{Fe}_2\text{N} \) in Fe-N alloys,\(^{17}\) may be useful.

In conclusion, we have successfully revealed the thermal decomposition process and kinetics of \( \alpha''-\text{Fe}_4\text{N} \) under inert gaseous conditions. The decomposition mechanism is solely intra-solid atomic rearrangements. The decomposition products are \( \alpha'-\text{Fe} \) and \( \gamma'-\text{Fe}_2\text{N} \) mixed at 4:1 (molar ratio), and the process...
can be well represented by the first order reaction model: 
\[ D = 1 - \exp(-k_{app}t) \] , where \( k_{app} \) [1/h] = exp(48.9 – 23.9 × 10^(-3)/T). The formation of \( \gamma’\)-Fe3N with a higher thermal stability is responsible for the irreversible nature of the thermal decomposition processes. To enhance the thermal stability of \( \alpha’\)-Fe10N2, it is indispensably necessary to somehow suppress the formation of the \( \gamma’\)-phase. Quantitative understanding of thermal stability of \( \alpha’\)-Fe10N2 given in this work will open ways to new applications such as a car motor magnet where higher working temperatures are necessary.

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Notes and references

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