**Enhanced Curie temperature and cooling efficiency in melt-extracted
Gd₅₀(Co_{69.25}Fe_{4.25}Si₁₃B_{13.5})₅₀ microwires**

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Abstract

We report enhancements of both Curie temperature and magnetic refrigerant capacity
in Gd₅₀(Co_{69.25}Fe_{4.25}Si₁₃B_{13.5})₅₀ microwires, which were fabricated by the
melt-extraction method. For a field change of 5 T, the maximum magnetic entropy
change ($-\Delta S_M^{\max}$), the refrigerant capacity (RC) and relative cooling power (RCP)
reached high values of 6.56 J·kg⁻¹·K⁻¹, 625 J·kg⁻¹ and 826 J·kg⁻¹, respectively. While
the RC is similar to those of our previously reported GdAlCo microwires, a much
broader working temperature range of ~126 K and a higher Curie temperature of 170
K make the Gd₅₀(Co_{69.25}Fe_{4.25}Si₁₃B_{13.5})₅₀ microwires more attractive for active
magnetic refrigeration.

Keywords: Melt-extraction; Microwire; Magnetocaloric effect; Magnetic
refrigeration.

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1. Introduction

Magnetocaloric effect (MCE) is an intrinsic characteristic of magnetic materials, which refers to a change of magnetic entropy in the material subjected to an external magnetic field [1]. The material that shows a decrease of magnetic entropy will release heat upon the application of an external magnetic field [2]. Conversely, the material that shows an increase of magnetic entropy will absorb heat when the external magnetic field is removed. As compared with traditional gas compression and expansion technique, magnetic refrigeration (MR) based on the MCE employs a solid magnetic substance as the refrigerant, leading to a higher efficiency and causing no damage to the atmospheric ozone layer. Therefore, MR is considered as an environmental friendly cooling technology [3]. In addition, MR only requires a magnetic field provided by a permanent magnet or an electromagnet or a superconductor instead of a compressor, which enabling an excellent mechanical reliability and resolving the issues of abrasion and mechanical noise in gas compression refrigerators [4].

Magnetic materials with rare-earth components showing normal [5, 6] or inverse MCEs [7] are widely explored in the MR technology due to their large magnetic moments, such as $\text{La}_{0.7-x}\text{Pr}_x\text{Ca}_{0.3}\text{MnO}_3$ [8], Er-Ho-Co [9, 10], and Ho-Er-Ni [11]. In particular, rare-earth based amorphous alloys such as Ho-, Dy-, Er-, Gd-based alloys exhibit large magnetic entropy changes ($-\Delta S_M$) over wide temperature ranges, resulting in the large refrigerant capacities (RC) [5]. As compared with polycrystals [6], amorphous materials usually possess higher RC values owing to the broadened

1 magnetic phase transitions as a result of structural disorder effect. Rapid solidification
2 technology is a common method for fabrication of earth-based bulk metallic glasses
3 [12] and ribbon-like [13] compounds with excellent magnetocaloric properties.
4 Moreover, the theoretical calculations of Kuz'min [14] have shown that the closely
5 packed cylindrical wires as refrigerants with high mechanical stability and low
6 porosity possess a higher operation frequency as compared to laminar-shaped or
7 chequer-board arranged refrigerants. Vuarnoz *et al.* [15] have also theoretically
8 demonstrated that the energy transfer efficiency can be enhanced in magnetic
9 refrigerators using microscale wire-shaped materials. However, producing amorphous
10 magnetic wires with diameters less than 1 mm using traditional fabrication techniques
11 has remained a challenging task. Applying a precision homemade melt-extraction
12 technique with greater quenching rates, we have been successful in preparing a new
13 class of high quality Gd-based microwires such as GdCoAl that possess enhanced
14 MCE and RC [16-21]. In these GdCoAl microwires, Al was used to enhance
15 amorphous structure and hence MCE, but decreased the Curie temperature of the
16 initial alloy. Our current efforts are to increase the Curie temperature and the
17 operation temperature range of such microwires for active magnetic refrigeration.

18 In this context, we propose to combine the excellent magnetic properties of Gd
19 and $\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5}$ to design and fabricate $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$
20 microwires using our melt-extraction method. It is generally accepted that Gd with a
21 large magnetic moment is a benchmark magnetocaloric material for near-room
22 temperature magnetic refrigeration [3], while $\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5}$ amorphous

1 microwires possess excellent glass forming ability and soft ferromagnetic
2 characteristic at ambient temperature for a wide range of advanced magnetic sensing
3 applications [22-24]. We show that as compared to the GdCoAl microwires, the
4 designed $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires possess large enhancements of both
5 the Curie temperature and the operation temperature range, which are desirable for
6 active magnetic refrigeration.

7

8 2. Experimental details

9 The raw materials used in this study were highly pure Gd (99.5% purity), Co (99.99%
10 purity), Fe (99.99% purity), Si (99.99% purity) and B (99.99% purity). Firstly, the
11 alloy rod with a nominal composition of $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ and a diameter
12 of 10 mm was obtained by a vacuum arc melting equipment under argon atmosphere.
13 Subsequently, $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires were prepared by the precision
14 homemade melt-drawing apparatus. The melt extraction process was carried out using
15 a copper wheel with a diameter of 320 mm and an edge of 60 °. The linear velocity of
16 the rim was fixed at 30 m/s and the feeding rate of the molten alloy was 10-15 $\mu\text{m/s}$.
17 The details of the preparation process can be found in previous paper of our group
18 [25]. Inset of Fig. 1a shows an optical image of the fabricated
19 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires.

20 The micro morphology of $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires was observed
21 using a field emission scanning electron microscope (SEM-Helios Nanolab 600i)
22 operating at 20 kV, and the EDS was used to confirm the composition of the

microwire. The microstructure of the microwire was identified by X-ray diffraction (XRD) using a D/MAX- γ B X-ray diffractometer (Cu/K α). Magnetic measurements were performed using a Quantum Design Magnetic Property Measurement System (SQUID-VSM).

3. Results and discussion

3.1. Structural characterization

As can be seen in inset of Fig. 1b, the fabricated Gd₅₀(Co_{69.25}Fe_{4.25}Si₁₃B_{13.5})₅₀ microwires possess a smooth surface, a high circular cross section, and no apparent Rayleigh wave with a uniform diameter of ~30 μ m. The XRD pattern of the microwires measured from 20° to 100° (2 θ) with a scanning speed of 2°/min is shown in Fig.1a. There is only a broad diffuse peak detected at the position of ~34° without any obvious crystal sharp peaks, indicating that the microwires possess a typical amorphous microstructure. The compositional analysis confirms the presence of Gd, Co, Fe and Si in the sample. However, the atomic percent of the sample differs from the nominal composition because the element B cannot be detected using EDS.

The amorphous structure of the microwires can also be predicted based on Inoue's three rules of thumb [26]: (1) Multi-component (e.g. five components) system; (2) significant atomic size mismatch: the atomic radii of Gd, Co, Fe, Si and B are about 0.178 nm, 0.126 nm, 0.125 nm, 0.111 and 0.082nm, respectively; (3) negative mixing heat: the mixing enthalpy is -22 kJ/mol for the Gd-Co pair, -1 kJ/mol for the Gd-Fe pair, -73 kJ/mol for the Gd-Si pair, -50 kJ/mol for the Gd-B pair [27]. The analysis

1 indicates that the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires possess a good
2 glass-forming ability (GFA).

3 3.2. Magnetic properties

4 [Fig. 2](#) (left hand) shows the temperature dependence of magnetization (M - T) for
5 the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires measured from [20](#) to 260 K under a
6 constant external field of 200 Oe. It can be seen that the ferromagnetic to
7 paramagnetic transition takes place **with** the increase of temperature. The derivation of
8 the M - T curve was analyzed to determine the Curie temperature of the microwires, as
9 shown in inset of [Fig. 2](#). The lowest point of the dM/dT curve corresponds to the
10 Curie temperature of [~170](#) K. It is interesting that the T_C of the
11 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires is ~ 70 K higher than those of our previously
12 reported Gd-Al-Co **amorphous** microwires ($T_C \sim 100$ K) [\[16-21\]](#). **It has been reported**
13 **that relative to GdCo binary alloys [28], the Al addition enhanced the MCE but**
14 **reduced the Curie temperature in GdCoAl ternary alloys [29]. In our present study, the**
15 **combination of Gd with $\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5}$ that possesses an excellent glass forming**
16 **ability and an excellent soft ferromagnetic characteristic above room temperature is**
17 **expected to retain high values of the Curie temperature.**

18 To further understand the magnetic behavior of a multi-component system like
19 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$, a H/M vs. T conversion curve based on the M - T curve
20 was constructed and the result is shown in [Fig. 2](#) (right hand). It can be seen that the
21 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwire follows the Curie-Weiss law above the T_C [\[30\]](#).
22 The paramagnetic Curie point is positive **which** indicating that the exchange

1 ferromagnetic interaction dominates below the T_C temperature. Based on the
 2 Curie-Weiss law, the Curie constant (C) and Curie-Weiss temperature (θ_p) can be
 3 calculated by fitting the line parts as indicated in Fig. 2 (right hand). The fitted result
 4 yields C of 4.19 emu·K/mol and θ_p of 186.5 K, respectively. Furthermore, the Curie
 5 constant can be expressed as

$$6 \quad C = \frac{nN_A g^2 J(J+1) \mu_B^2}{3k_B} \quad (4)$$

7 and the effective magnetic moment (μ_{eff}) is calculated by:

$$8 \quad \mu_{eff} = g \sqrt{J(J+1)} \mu_B, \quad (5)$$

9 where n is the amount of substance for the fiber composition, N_A is the Avogadro
 10 constant, g is the Lande factor, J is the total angular momentum, k_B is Boltzmann
 11 constant and μ_B is Bohr magneton. From these relationships we obtained the μ_{eff} of
 12 $\sim 5.8 \mu_B$ for the $Gd_{50}(Co_{69.25}Fe_{4.25}Si_{13}B_{13.5})_{50}$ microwire. The obtained effective
 13 magnetic moment is mainly induced by the interaction of magnetic moments between
 14 transition metal (TM) elements with 3d-electrons and rare-earth (RE) element with
 15 4f-electrons [30]. This value is lower than that of theoretical value ($\sim 6.3 \mu_B$) and the
 16 $Gd_{60}Co_{15}Al_{25}$ microwire ($\sim 6.9 \mu_B$) [19]; this is expected that the Gd amount is larger
 17 in the latter case. It is worth noting that the Curie temperature of the
 18 $Gd_{50}(Co_{69.25}Fe_{4.25}Si_{13}B_{13.5})_{50}$ microwire (~ 170 K) is greater than that of the
 19 $Gd_{60}Co_{15}Al_{25}$ microwire (~ 100 K), which indicating enhanced ferromagnetic
 20 interaction in case of the $Gd_{50}(Co_{69.25}Fe_{4.25}Si_{13}B_{13.5})_{50}$ microwire due to the
 21 multi-component alloying effect.

22 In order to determine the nature of the ferromagnetic-paramagnetic phase

1 transition and also the MCE for the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires, we
 2 measured the isothermal M - H curves around the Curie temperature (Fig. 3a). The
 3 M - H isotherms are converted into the modified Arrott plots (H/M vs. M^2), as shown in
 4 Fig. 3b. It can be observed that the tangent slopes of all the curves are positive,
 5 indicating a second-order phase transition of the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$
 6 microwire and in accordance with the Banerjee criterion [31]. In second-order phase
 7 transition materials, the thermal and magnetic hysteresis are often negligible, which
 8 are beneficial for the operation of active magnetic refrigerators [17].

9 3.3. Magnetocaloric properties

10 The magnetic entropy changes of $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires were
 11 calculated from the isothermal magnetization curves (Fig. 3a) using Maxwell
 12 relationship [32]:

$$13 \quad \Delta S_M(T, H) = S(T, H) - S(T, 0) = \int_0^{H_{\max}} \left(\frac{\partial M}{\partial T} \right)_H dH, \quad (6)$$

14 where S represents the magnetic entropy and $H_{\max}$ represents the maximum external
 15 magnetic field. The temperature dependence of magnetic entropy change ($-\Delta S_M(T, H)$)
 16 at different applied field changes is shown in Fig. 4. The maximum magnetic entropy
 17 change, ($-\Delta S_M^{\max}$), reaches a large value of $\sim 6.56 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ at $\sim 170 \text{ K}$ for a magnetic
 18 field change of 50 kOe. This value is lower than that of $\sim 10.3 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ reported
 19 previously by us for the $\text{Gd}_{53}\text{Al}_{24}\text{Co}_{20}\text{Zr}_3$ microwires [17]. This decrease in $\Delta S_M^{\max}$ for
 20 the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires can be related to the decrease of the
 21 effective magnetic moment as discussed above. However, the full width at half
 22 maximum of the $-\Delta S_M(T, H)$ curves ($\sim 126 \text{ K}$) for the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$

1 microwires is much greater as compared to that (~83 K) of the $\text{Gd}_{55}\text{Al}_{20}\text{Co}_{25}$
2 microwires. This feature makes the former more desirable for practical cooling
3 applications.

4 To explore the relationship between the maximum magnetic entropy change and
5 the applied magnetic field near the magnetic phase transition temperature for the
6 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires, the $\Delta S_{\text{M}}^{\text{max}}(H)$ at $T = 170$ K is plotted and
7 fitted to the following expression [33]:

$$8 \quad -\Delta S_{\text{M}}^{\text{max}} \propto H^n, \quad (7)$$

9 where n is a local exponent. The fitted result is shown in Fig. 5a, which yields $n =$
10 0.77, in good agreement with those reported previously for the Gd-Al-Co microwires
11 [16-21]. This value of n is also close to that reported previously for typical Fe-based
12 amorphous alloys ($n = 0.75$) [34], but deviates from the mean-field theoretical value
13 ($n = 0.67$) [33]. This deviation may arise from the structural and magnetic disorders
14 caused by the multi-component alloying effect.

15 It is worth noting that $(-\Delta S_{\text{M}}^{\text{max}})$ is just one of parameters for evaluating the
16 magnetocaloric property of a material. Some of the first-order phase transition
17 materials show $\Delta S_{\text{M}}^{\text{max}}$ of more than $10 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ but their working temperature
18 ranges are limited to only a few Kelvins and the ΔS_{M} decreases sharply when the
19 temperature deviates from the phase transition point [35, 36]. However, both the
20 first-order and the second-order phase transition materials show the peak-shaped
21 curves of $\Delta S_{\text{M}}(T)$. Therefore, the full width at half maximum of the magnetic entropy
22 change vs. temperature curve (δT_{FWHM}) is defined as the operating temperature range

1 of a material. Obviously, the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires show broad
 2 triangle $-\Delta S_{\text{M}}(T, H)$ curves especially at high applied fields as exhibited in Fig. 4 and
 3 an extremely large working temperature range of ~ 126 K is obtained at $\mu_0\Delta H = 5$ T.
 4 This δT_{FWHM} value is larger than those of GdAlCo microwires and Gd-based bulk
 5 metallic glasses [37]. The excellent working temperature range of the microwires is
 6 regarded as a result of both the size effect and the good glass forming ability.
 7 Moreover, Liu *et al.* have proposed a model that the magnetic phase transitions in
 8 amorphous materials would be broadened due to the fluctuation of exchange integrals
 9 as a result of structural disorder that is always present in amorphous alloys [38].

10 For a cooling application, it is essential for a magnetocaloric material possessing
 11 a large magnetic entropy change over a wide working temperature range. In reality,
 12 however, one must consider balancing these two factors. In this regard, the refrigerant
 13 capacity (RC) defined by integrating the area of the $-\Delta S_{\text{M}}$ curves enclosed within
 14 FWHM temperatures and/or the relative cooling power (RCP) defined as the product
 15 of $-\Delta S_{\text{M}}$ and δT_{FWHM} are often employed for characterizing the cooling efficiency of a
 16 material. RC and RCP can be expressed as follows [17]:

$$17 \quad RC = \int_{T_1}^{T_2} -\Delta S_{\text{M}}(T) dT, \quad (8)$$

$$18 \quad RCP = -\Delta S_{\text{M}}^{\text{max}} * \delta T_{\text{FWHM}} = -\Delta S_{\text{M}}^{\text{max}} (T_2 - T_1), \quad (9)$$

19 where T_1 and T_2 are the onset and offset temperatures of δT_{FWHM} , respectively. The
 20 value of RC is usually $\sim 3/4$ of the RCP due to the wide triangular peak of $-\Delta S_{\text{M}}(T, H)$
 21 curves [38]. The calculated results of RC and RCP for the
 22 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires are shown in Fig. 5b, and which all are also

1 summarized in Table 1 combined with δT_{FWHM} . The RC and RCP values of the
2 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires are $\sim 625 \text{ J}\cdot\text{kg}^{-1}$ and $826 \text{ J}\cdot\text{kg}^{-1}$ at $\mu_0\Delta H = 5 \text{ T}$,
3 respectively. Compared to GdAlCo microwires [16-21], the present microwires
4 possess smaller $-\Delta S_{\text{M}}^{\text{max}}$ values but equal or even larger RC and RCP values (see
5 Table 1), making them more desirable for active magnetic refrigeration. Some
6 intermetallic compounds such as TdGa and $\text{Gd}_{0.8}\text{Er}_{0.2}\text{Ga}$, in the same temperature
7 range of interest, show similar magnetocaloric properties and even larger RC values
8 than the present microwires; this is due to the presence of two successive transitions
9 which are the spin-reorientation (SR) and second-order ferromagnetic-paramagnetic
10 (FM-PM) that enhanced the δT_{FWHM} and hence the RC values [39, 40].

11 4. Conclusions

12 In summary, the melt-extracted $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires show
13 amorphous microstructures and good metallic glass forming ability. These microwires
14 possess an improved T_{C} temperature of $\sim 170 \text{ K}$ as compared to the GdAlCo
15 microwires ($\sim 100 \text{ K}$), due to the multi-component alloying effect. The
16 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires also possess large values of RC $\sim 625 \text{ J}\cdot\text{kg}^{-1}$
17 and RCP $\sim 826 \text{ J}\cdot\text{kg}^{-1}$ at $\mu_0\Delta H = 5 \text{ T}$, which are equal and even larger as compared to
18 the previously reported GdAlCo microwires. The excellent magnetic and
19 magnetocaloric properties of the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires make them
20 very attractive for active magnetic refrigeration in the nitrogen temperature range.

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Table 1. The magnetocaloric parameters of the present wires, and the wires and some intermetallic compounds reported previously in the literature.

Composition	T_C (K)	$\mu_0\Delta H$ (T)	$-\Delta S_M^{\max}$ (J·kg ⁻¹ ·K ⁻¹)	RC (J·kg ⁻¹)	RCP (J·kg ⁻¹)	δT_{FWHM} (K)	Ref.
Gd ₅₀ (Co _{69.25} Fe _{4.25} Si ₁₃ B _{13.5}) ₅₀	170	5	6.56	625	826	126	Present
Gd ₅₀ Al ₃₀ Co ₂₀	86	5	10.1	672	--	90	[16]
Gd ₅₃ Al ₂₄ Co ₂₀ Zr ₃	96	5	10.3	733	--	--	[17]
Gd ₅₅ Al ₂₅ Co ₂₀	100	5	9.7	652	--	--	[18]
Gd ₆₀ Co ₁₅ Al ₂₅	101	5	9.7	732	973	--	[19]
Gd ₆₀ Al ₂₀ Co ₂₀	109	5	10.1	681	915	91	[20]
Gd ₅₅ Al ₂₀ Co ₂₅	110	5	9.7	580	804	83	[21]
TdGa*	154	5	5.9	620.6	--	--	[36]
Gd _{0.8} Er _{0.2} Ga*	168	5	5.6	715.3	--	185.5	[37]

* Intermetallic compounds

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14

1 **Figure Captions**

2 **Fig. 1** a) the XRD pattern of melt-extracted $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires
3 and its inset shows an image of these microwires; b) an EDS spectrum (main panel)
4 and an SEM image of the $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires (inset).

5 **Fig. 2** The temperature dependence of magnetization at a field of 200 Oe (left hand)
6 and the curve constructed by the Curie-Weiss law (right hand). Inset shows the dM/dT
7 vs. T curve.

8 **Fig. 3** a) The isothermal magnetization (M - H) curves of the
9 $\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$ microwires at different temperatures and b) is the
10 corresponding Arrott conversion H/M vs. M^2 curves.

11 **Fig. 4** The temperature dependence of magnetic entropy change ($-\Delta S_M$) for different
12 applied field changes.

13 **Fig. 5** a) the fitted result of the maximum magnetic entropy change ($-\Delta S_M^{\max}$) vs.
14 magnetic field; b) the calculated RC and RCP values at different applied fields.

15

16

17

18

a)

Intensity (a.u.)

$\text{Gd}_{50}(\text{Co}_{69.25}\text{Fe}_{4.25}\text{Si}_{13}\text{B}_{13.5})_{50}$

— XRD Result

20

40

60

80

100

2θ

b)

507

380

253

126

0

Element	Wt%	At%
SiK	01.54	05.95
GdL	75.72	52.10
FeK	02.03	03.94
CoK	20.70	38.01
Matrix	Correction	ZAF

Gd**Co****Gd****Si****Co****Fe**

Energy - keV

0.00

1.00

2.00

3.00

4.00

5.00

6.00

7.00

8.00

9.00

10.0

a)

a)

b)