Article

Influence of Covalent Element B and Si Addition on Magnetocaloric Properties of Gd-Co-Fe-(B,Si) Amorphous Alloys

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Abstract: The effect of covalent element addition on the magnetic and magnetocaloric properties of ferrimagnetic Gd₆₀Co₂₀Fe₂₀ amorphous alloy was studied. Particularly, the co-doping of B and Si promoted the magnetocaloric performance (with a larger magnetic entropy change $|\Delta S_M|$ at higher working temperature) of the initial Gd₆₀Co₂₀Fe₂₀ amorphous alloy. This is possibly ascribed to the modified magnetic transition behavior. Additionally, the broadened magnetocaloric effect with $|\Delta S_M|$ of 2.25 J kg^{−1} K^{−1} at 222.5 K under a magnetic field change of 0–2 T and high relative cooling power of 396.0 J kg^{−1} were obtained for (Gd_{0.6}Co_{0.2}Fe_{0.2})₉₅B₂Si₃. These properties reveal that the material could be a good candidate as a magnetic refrigerant suitable for active magnetic refrigerators.

Keywords: Gd-Co-Fe amorphous alloy; covalent element addition; magnetocaloric performance; magnetic refrigeration

Citation: Zhang, H.; Xu, Y.; Zhang, Z.; Tan, J.; Zhang, X.; Peng, H.; Xiang, X.; Li, H.; Xia, A.; Li, W. Influence of Covalent Element B and Si Addition on Magnetocaloric Properties of Gd-Co-Fe-(B,Si) Amorphous Alloys. *Metals* **2022**, *12*, 386. <https://doi.org/10.3390/met12030386>

Academic Editor: Volodymyr A. Chernenko

Received: 5 January 2022

Accepted: 21 February 2022

Published: 23 February 2022

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1. Introduction

Compared with traditional gas compression refrigeration, magnetic refrigeration (MR) exhibits advantages of environmental friendliness, compactness, less noise, and higher efficiency and has attracted worldwide attention [1]. The working principle of MR is the intrinsic magnetocaloric effect (MCE) of magnetic materials, meaning when an external magnetic field is applied isothermally, the magnetic moment is parallelly aligned and the magnetic entropy decreases. Under the adiabatic condition, the total entropy of the magnetic materials remains unchanged, so the lattice and electron entropy increase to balance the variation in magnetic entropy, and then the system temperature becomes higher. The reverse process occurs when the magnetic field is removed. Therefore, the isothermal magnetic entropy change $|\Delta S_M|$ and the adiabatic temperature change ΔT_{ad} are important parameters used to characterize the MCE [2].

Most of the near-room-temperature magnetic refrigerants are ferromagnetic, and the MCE reaches its maximum close to the Curie temperature (T_C) [3]. Based on the order of magnetic transition, magnetocaloric materials can be classified into two types, namely first-order magnetic transition (FOMT) materials and second-order magnetic transition (SOMT) materials. FOMT materials undergo a discontinuous change in magnetization with varying temperature, so generally, they show a large $|\Delta S_M|$, e.g., Gd₅Si₂Ge₂ [4], Mn-Fe-P-Si alloy [5], Ni-Mn-Si-based alloy [6], and LaFe_{11.83}Mn_{0.32}Si_{1.30}H_x [7]. However, their drawbacks are the sharp drop in $|\Delta S_M|$ when the temperature deviates from T_C , and the existence of magnetic and thermal hysteresis, which would reduce the refrigeration efficiency. In the case of SOMT materials, the magnetization changes with temperature continuously. Although their $|\Delta S_M|$ is lower than that of FOMT materials, they possess many

merits, such as low thermal and magnetic hysteresis and a wider working temperature range, ensuring good magnetocaloric performance. The representative material is pure metal Gd, known as “prototype refrigerant” [3].

In general, magnetic amorphous alloys belong to SOMT materials. Except for the above-mentioned advantages, the unique atomic structure (long-range disordered and short-range ordered) provides amorphous alloys with properties of compositional tailoring, low eddy current losses, high corrosion resistance, etc. [8]. In the past 2 decades, Gd- and Fe-based amorphous alloys have attracted more attention as candidates for near-room-temperature magnetic refrigeration [1]. Among Gd-based amorphous alloys, the ferrimagnetic Gd-Co-Fe alloy system shows higher magnetocaloric performance than many Fe-based samples near room temperature [9]. Under an applied field changing from 0 to 2 T, the peak value of the magnetic entropy change ($|\Delta S_M^{pk}|$) of Gd₄₈Co₅₀Fe₂ and Gd₅₀Co₄₅Fe₅ amorphous alloys is 1.98 and 1.85 J kg^{−1} K^{−1} at temperatures of 297 and 289 K, respectively [10,11].

However, the magnetic and magnetocaloric properties of Gd-Co-Fe amorphous alloys are sensitive to the Fe content: (1) When the element Co is substituted by a small amount of Fe, T_C increases to be closer to room temperature and $|\Delta S_M|$ decreases moderately [11,12]; (2) further replacement of Co with Fe (e.g., Gd₆₀Co₂₀Fe₂₀) may cause the change in the magnetic exchange constant of antiferromagnetic Gd-Fe interaction (J_{Gd-Fe}) and then the deviation of the working temperature from T_C , which means the magnetic entropy change and working temperature drop simultaneously [13–15]. It has been reported that the magnetic transition behavior can be modified by adding covalent element B to Gd-Fe amorphous alloys, owing to the increase in J_{Gd-Fe} and decrease in the Fe magnetic moment [16]. In this study, the influence of adding covalent elements B and Si on the magnetic and magnetocaloric properties of Gd₆₀Co₂₀Fe₂₀ amorphous alloy was studied, with the expectation to improve its magnetocaloric performance by modifying the internal magnetic properties.

2. Materials and Methods

The raw materials used to prepare the master alloys with nominal compositions of Gd₆₀Co₂₀Fe₂₀ and (Gd_{0.6}Co_{0.2}Fe_{0.2})₉₅B_{*x*}Si_{5−*x*} (*x* = 0, 2, 5) were pure metals Gd (99.9 wt%), Co (99.9 wt%), and Fe (99.9 wt%) and the prealloys of BFe and SiFe (the mass ratios of B to Fe and Si to Fe in BFe and SiFe were 17.62:81.46 and 22.25:74.53, respectively). The master alloys were produced using a vacuum arc-melting furnace under the protection of a high-purity argon atmosphere, and the ingots were remelted four times to ensure their compositional homogeneity. The small pieces of the ingots were put into quartz tubes and remelted through high-frequency induction in a high-purity argon atmosphere, and then ribbons with a width of 1.5–2 mm and a thickness of 25–30 μm were manufactured by the single roller melt-spinning method at a wheel surface speed of 50 m/s.

Phase structure characterization of the as-spun ribbons was carried out by X-ray diffraction (XRD; D8 Advance, Bruker, Karlsruhe, Germany) using Cu Kα radiation ($\lambda = 0.15418$ nm) and a 2θ range of 20°–80°. Thermal properties were measured by differential scanning calorimetry (DSC; STA 449F3, NETZSCH, Selb, Germany) at a heating rate of 0.33 K/s with high-purity argon gas purged. In-plane magnetic hysteresis loops at different temperatures were detected by a magnetic property measurement system (MPMS; MPMS 3, Quantum Design, San Diego, CA, USA). To investigate the magnetic transition behavior of the samples, the temperature dependence of the magnetization (M – T) curve was recorded during the heating process from 100 K to 380 K under a magnetic field of 0.001 T after zero-field cooling (ZFC). The magnetocaloric performance of the ribbons was determined by the temperature dependence of the magnetic entropy change $|\Delta S_M|$ obtained through indirect measurement using the physical property measurement system (PPMS; PPMS-9T, Quantum Design, San Diego, CA, USA). The magnetization isotherms (M – H curves) at selected temperatures were observed under the applied magnetic field changing from 0 to

2 T. Subsequently, according to the M – H curves, the $|\Delta S_M|$ was calculated by the Maxwell relation [17]:

$$\Delta S_M(T, H) = S_M(T, H) - S_M(T, 0) = \int_0^H \left\{ \frac{\partial M(T, H)}{\partial T} \right\}_H dH \quad (1)$$

Usually, the numerical approximation of the integral of the M – H curves with small, discrete temperature intervals was used as the following equation [18]:

$$\Delta S_M \left(\frac{T_{i+1} + T_i}{2} \right) = \sum_i \frac{M_{i+1} - M_i}{T_{i+1} - T_i} \Delta H_i, \quad (2)$$

where M_i and M_{i+1} are experimental values of magnetization at temperatures T_i and T_{i+1} under an applied magnetic field H_i , respectively. All the measurements of magnetic properties were performed with the magnetic field transverse to the alloy ribbons.

3. Results and Discussion

3.1. Structural and Thermal Characterization

Figure 1a exhibits the XRD patterns of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) as-spun ribbons. The typical broadened diffuse peaks indicate the amorphous structure of the samples. However, a few minor sharp peaks can be found. The ones marked with triangles and circles are possibly associated with Gd_4Co_3 and $\text{Gd}_{12}\text{Co}_7$ phases, respectively [19]. The precipitation of different crystalline phase resulted in the compositional variation of the amorphous matrix and a slight shift of the diffuse peak for different alloys.

Figure 1. (a) XRD patterns and (b) DSC curves of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) as-spun ribbons.

The exothermic peak (corresponding to crystallization) on the DSC curves shown in Figure 1b confirms the amorphous structure of the as-spun ribbons. The initial crystallization temperature (T_x) was determined by the intersection of the extrapolated base line and the steepest tangent to the first exothermic peak. In this research, T_x of $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{Si}_5$, $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$, and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_5$ was 555, 596, and 597 K, respectively,

higher than that of $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ (544 K). Therefore, the addition of covalent element B or Si enhances the thermal stability of $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous alloys, and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ possesses the best thermal stability [20]. In addition, the T_x of each sample was high enough to maintain its amorphous structure at room temperature. At higher temperature, more exothermic peaks were obtained, which is ascribed to the formation of different phases at different stages of heating [21]. With increasing B content, the exotherms became sharper and moved closer to each other.

3.2. Magnetic Properties

Figure 2a displays the ZFC M - T curves of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) amorphous alloys under a magnetic field of 0.001 T, respectively. With increasing temperature, the magnetic transition from ferrimagnetic to paramagnetic could be observed in all the alloys near the Curie temperature (T_C). In this study, we used the inflection point method to determine T_C , i.e., the temperature corresponding to the minimum of the dM/dT - T curves, as illustrated in Figure 2b. For $x = 0, 2$, and 5, the values of T_C were 256, 230, and 212 K, lower than that of $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ ($T_C = 338$ K). Moreover, $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ showed a broad magnetic transition with respect to temperature, which became narrower after adding B and Si. The magnetic transition behavior is closely related to the internal magnetic exchange interaction [11,15,22,23], and the phenomenon can be interpreted as follows: The introduction of B weakens the magnetic moment of Fe and enhances the antiferromagnetic exchange interaction between Gd and Fe, and then results in a reduction in T_C and a sharpened magnetic transition process [16]. The covalent element Si may have an analogous effect.

Figure 2. M - T curves of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) amorphous alloys under an applied magnetic field of (a) 0.001 T and (b) the correlating curves of dM/dT vs. T .

3.3. Magnetocaloric Properties

The isothermal magnetization (M - H) curves of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous alloys at different selected temperatures under an applied magnetic field change of 0–2 T are shown in Figure 3a–d. In this study, a temperature interval of 15 K and 2 K (or 5 K) was chosen for the temperature region far away from and in the vicinity of T_C , respectively. It can be seen that with increasing temperature, the magnetization decreased and the magnetic state gradually changed from ferrimagnetism to paramagnetism. ΔS_M can be calculated from the data of the M - H curves on basis of the Equation (2), and the temperature dependence of $|\Delta S_M|$ is shown in Figure 4. Under the magnetic field changing from 0 to 2 T, the $|\Delta S_M^{pk}|$ of $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{Si}_5$, $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$, and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_5$ amorphous alloys was 1.92, 2.25, and 2.27 $\text{J kg}^{-1} \text{K}^{-1}$, respectively, higher than that of $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ (1.71 $\text{J kg}^{-1} \text{K}^{-1}$). The tem-

perature corresponding to $|\Delta S_M^{pk}|$ under 2 T was denoted as T_{pk} , and the values of T_{pk} for $x = 0, 2$, and 5 and $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ were 205, 222.5, 202.5, and 205 K, respectively. Therefore, the co-addition of Si and B not only improves $|\Delta S_M^{pk}|$ but also raises the working temperature. The large inconsistency between T_{pk} and T_C is worth noting, which is possibly attributed to the local inhomogeneity in the amorphous matrix, such as nanocrystalline (observed in Figure 1a), clusters, or free volume [15,24].

Figure 3. The M - H curves of the (a) $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous ribbons with $x =$ (b) 0, (c) 2, and (d) 5 at selected temperatures.

As listed in Table 1, the $|\Delta S_M^{pk}|$ of the $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ amorphous ribbon was larger than that of $\text{Gd}_{60}\text{Co}_{30}\text{Fe}_{10}$, $\text{Gd}_{75}(\text{Fe}_{0.75}\text{Co}_{0.25})_{25}$, and some Fe-based amorphous counterparts with similar T_{pk} but lower than that of Gd-Co-based amorphous alloys with a small amount of Fe or without Fe, such as $\text{Gd}_{60}\text{Co}_{35}\text{Fe}_5$ and $\text{Gd}_{56}\text{Co}_{44}$. Another parameter used to evaluate the MCE is the relative cooling power (RCP), which represents the heat transfer between the hot and cold reservoirs in an ideal refrigeration cycle, and can be described as:

$$\text{RCP} = |\Delta S_M^{pk}| \times \Delta T_{FWHM}, \quad (3)$$

where ΔT_{FWHM} is defined as the full width at half maximum of the $|\Delta S_M|$ - T curve [1]. A large RCP of 396.0 J kg^{-1} was obtained in the $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ sample, and the value of $|\Delta S_M|$ was nearly constant ($2.20 \pm 0.05 \text{ J kg}^{-1} \text{ K}^{-1}$) among a wide temperature range of 198–233 K, i.e., the so-called table-like MCE, which makes it more suitable for Ericsson-cycle refrigeration [25]. It is probable that the exchange interaction of local magnetic clusters with different ordering temperature results in a broad magnetic transition, leading to the broadened $|\Delta S_M|$ - T curve and significant RCP enhancement [11]. In this study, the $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ amorphous alloy exhibited superior performance compared to

the partially crystallized $\text{Gd}_{55}\text{Ni}_{10}\text{Co}_{35}$ ($|\Delta S_M|$ maintained the value of $\sim 2.03 \text{ J kg}^{-1} \text{ K}^{-1}$ within 179–205 K) and dual-phase $\text{Gd}_{48}\text{Co}_{50}\text{Nb}_2$ ribbons ($|\Delta S_M|$ maintained its value of $\sim 1.7 \text{ J kg}^{-1} \text{ K}^{-1}$ within a temperature range of 220–265 K) [26,27].

Figure 4. The correlation between magnetic entropy change and temperature of the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous alloys.

Table 1. Magnetic and magnetocaloric properties of various materials with a similar working temperature range (A and C indicate amorphous and crystalline structures, respectively).

Alloys	Structure	T_{C} (K)	T_{pk} (K)	$ \Delta S_M^{pk} $ (J kg ⁻¹ K ⁻¹)	ΔT_{FWHM} (K)	RCP (J kg ⁻¹)	Reference
		$\mu_0 H = 0.001 \text{ T}$		$\mu_0 H = 2 \text{ T}$			
(Gd _{0.6} Co _{0.2} Fe _{0.2}) ₉₅ B ₅	A	212	202.5	2.27	162	367.7	This work
(Gd _{0.6} Co _{0.2} Fe _{0.2}) ₉₅ B ₂ Si ₃	A	230	222.5	2.25	176	396.0	This work
(Gd _{0.6} Co _{0.2} Fe _{0.2}) ₉₅ Si ₅	A	256	205	1.92	190	364.8	This work
Gd ₆₀ Co ₂₀ Fe ₂₀	A	338	205	1.71	178	304.4	This work
Gd ₄₈ Co ₅₀ Nb ₂	A	220/264	~220	1.7	145	~246.5	[26]
Gd ₅₅ Ni ₁₀ Co ₃₅ (533 K annealing)	A + C	212	212	2.03	148	~300	[27]
Fe ₈₉ Co ₁ Sc ₁₀	A	196	210	1.24	182	225.7	[28]
(Fe ₉₃ Zr ₇) ₈₉ H ₁₁	A	200	~215	1.008	145.6	146.75	[29]
Gd ₇₅ (Fe _{0.75} Co _{0.25}) ₂₅	A + C	223	~220	2.0	-	-	[30]
Gd ₆₀ Co ₃₀ Fe ₁₀	A	239	222.5	2.08	154	~320	[31]
Gd ₆₀ Co ₃₅ Fe ₅	A	222	222.5	2.91	104	~303	[31]
Gd ₅₆ Co ₄₄	A	216	~215	3.34	85	~284	[32]

To determine the magnetic transition behavior in the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous alloys, Arrott plots (M^2 vs. H/M) converted from the isotherms are illustrated in Figure 5. According to the Banerjee criterion, the second-order transition can be identified when the slope of all the plots is positive, while the negative slope corresponds to the first-order transition [33]. In this case, all the slopes of Arrott plots were positive, which demonstrates the magnetic phase transition is of the second order. Figure 6 shows the hysteresis loops detected at 10, 200, 300, and 400 K for $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and

(Gd_{0.6}Co_{0.2}Fe_{0.2})₉₅B_xSi_{5-x} ribbons. The samples were almost soft magnetic with negligible hysteresis at 10 and 200 K and were paramagnetic at 400 K.

Figure 5. Arrott plots of amorphous alloys, (a) Gd₆₀Co₂₀Fe₂₀ and (Gd_{0.6}Co_{0.2}Fe_{0.2})₉₅B_xSi_{5-x} with $x =$ (b) 0, (c) 2, and (d) 5, derived from the M - H isotherms.

For the second-order magnetic phase transition, a universal relation of the field dependence of the magnetic entropy change was proposed by Oesterreicher and Parker, as the following equation [34]:

$$|\Delta S_M| \propto H^n, \quad (4)$$

where n is an exponent correlated with both H and T and can be locally calculated as:

$$n(H, T) = \frac{d \ln |\Delta S_M|}{d \ln H} \quad (5)$$

In the particular case of $T = T_C$ or T_{pk} , the n exponent becomes field independent [35]. Figure 7 exhibits the fitting results of the $\ln |\Delta S_M^{pk}|$ vs. $\ln H$ plots, and the values of $n(T_{pk})$ for the Gd₆₀Co₂₀Fe₂₀ and (Gd_{0.6}Co_{0.2}Fe_{0.2})₉₅B_xSi_{5-x} ($x = 0, 2, 5$) amorphous alloys were 0.93, 0.95, 0.87, and 0.87. It can be found all the n exponents deviate from the value of $2/3$ corresponding to mean field theory and the value of 0.72 ± 0.05 predicted in some amorphous alloys [36–38] but are close to the values observed in some Fe-containing Gd-based metallic glasses, e.g., Gd₅₀Co₄₅Fe₅ ($n = 0.837$) [10] and Gd₆₀Fe₂₀Al₂₀ ($n = 0.869$) [14]. The deviation is probably ascribed to the local inhomogeneity of the structure, since the critical exponents for the mean-field model are highly sensitive to the microstructure of the amorphous alloys [10,14,39].

Figure 6. Magnetic hysteresis loops of (a) $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and (b–d) $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) amorphous alloys at different temperatures.

Figure 7. Ln–Ln plots of the field dependence of $|\Delta S_M^{pk}|$ with the calculated $n(T_{pk})$ exponent for the $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ amorphous ribbons.

4. Conclusions

To summarize, $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ and $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_x\text{Si}_{5-x}$ ($x = 0, 2, 5$) amorphous alloy ribbons were fabricated, and their magnetic and magnetocaloric properties were investigated. The addition of covalent B or Si to $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ causes a reduction in T_C and sharpens the magnetic transition process. Especially, $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ co-doped with B and Si exhibits enhanced magnetocaloric performance with a larger $|\Delta S_M^{pk}|$ of $2.25 \text{ J kg}^{-1} \text{K}^{-1}$ at a higher working temperature of 222.5 K under an applied field change

of 0–2 T. Due to the existence of a small amount of Gd_4Co_3 or $\text{Gd}_{12}\text{Co}_7$ phase precipitated from the amorphous matrix, the local structural inhomogeneity leads to a broadened $|\Delta S_M|$ – T curve and a high RCP of 396.0 J kg^{-1} . The results indicate that the co-addition of B and Si to $\text{Gd}_{60}\text{Co}_{20}\text{Fe}_{20}$ modifies the magnetic transition behavior and improves the magnetocaloric properties of the material, making the $(\text{Gd}_{0.6}\text{Co}_{0.2}\text{Fe}_{0.2})_{95}\text{B}_2\text{Si}_3$ amorphous alloy a better candidate for magnetic refrigeration applications.

Author Contributions: Conceptualization, H.Z.; methodology, H.Z., Y.X. and Z.Z.; validation, H.Z., A.X. and W.L.; formal analysis, Y.X., Z.Z., H.P. and X.X.; investigation, Y.X., J.T., X.Z. and H.Z.; resources, A.X. and W.L.; data curation, H.Z. and H.L.; writing—original draft preparation, H.Z., Y.X. and Z.Z.; writing—review and editing, H.Z. and Y.X.; visualization, H.Z., Y.X. and Z.Z.; supervision, H.Z., A.X. and W.L.; project administration, H.Z.; funding acquisition, H.Z., H.P. and X.X. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by the Natural Science Foundation of China (grant no. 51701003) and the Innovation and Entrepreneurship Training Program for College Students of the Anhui University of Technology (grant nos. S201910360193 and 202110360023).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Authors would like to express gratitude to Xuguang Liu (from the Instruments Center for Physical Science, University of Science and Technology of China) and Wensen Wei (from the Hefei Institutes of Physical Science, Chinese Academy of Science) for help with performing PPMS and MPMS analyses, respectively.

Conflicts of Interest: The authors declare no conflict of interest.

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