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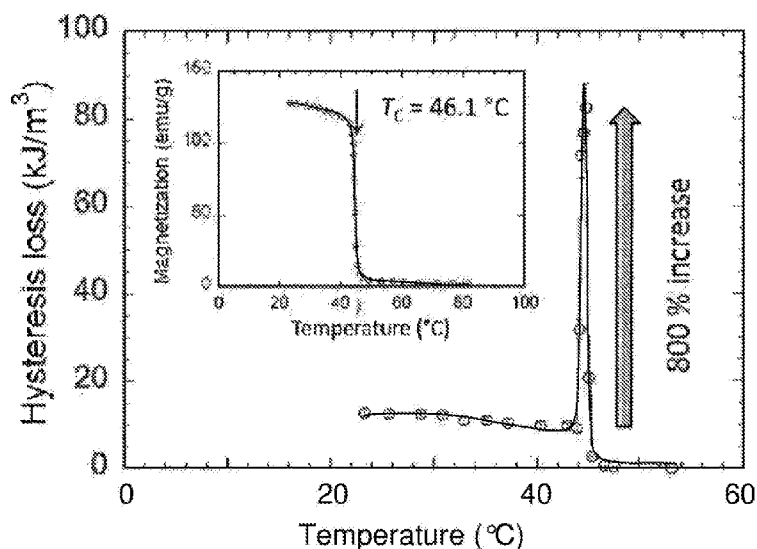


Fig. 4

(57) Abstract: A magnetic heating system is disclosed including ferromagnetic material that exhibits a first-order magnetic transition and a magnetic field generator adapted to apply an alternating magnetic field to the ferromagnetic material to induce heat emission from the ferromagnetic material. The first-order magnetic transition is accompanied by an abrupt change in the spontaneous magnetization. This abrupt change provides a significantly enhanced heating effect just below the magnetic transition temperature, which temperature can be selected or tuned depending on desired heating purposes such as hyperthermia therapy.

"Magnetic material for heating"

Cross-Reference to Related Applications

[0001] The present application claims priority from Australian Provisional Patent Application No 2013905012 filed on 20 December 2013, the content of which is incorporated herein by reference.

Technical Field

[0002] The present disclosure relates to magnetic materials and remote heating using magnetic materials.

Background

[0003] Magnetic materials such as superparamagnetic materials (e.g., magnetite nanoparticles) and magnetic materials exhibiting a second-order magnetic transition (e.g., metallic Iron and ferrites) have been used for remote heating. A magnetic field is applied to the magnetic material which induces heat output from the magnetic material.

[0004] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present disclosure as it existed before the priority date of each claim of this application.

Summary

[0005] In one aspect, the present disclosure provides a magnetic heating system comprising: ferromagnetic material exhibiting a first-order magnetic transition; and a magnetic field generator adapted to apply an alternating magnetic field to the ferromagnetic material to induce heat emission from the ferromagnetic material.

[0006] In another aspect, the present disclosure provides a method of heating comprising: applying an alternating magnetic field to a ferromagnetic material to induce heat

emission from the ferromagnetic material, the ferromagnetic material exhibiting a first-order magnetic transition.

[0007] A heating system and method according to the present disclosure can provide a substantially stronger heating effect than existing arrangements by utilising an extraordinary magnetic transition process known as the first-order magnetic transition. The ferromagnetic material of the present disclosure exhibits a first-order magnetic transition and this is accompanied by an abrupt change in the spontaneous magnetization. This abrupt change provides a significantly enhanced heating effect just below the magnetic transition temperature, also known as the Curie temperature (T_C), which temperature may be selected or tuned depending on desired heating purposes.

[0008] Under corresponding magnetic field conditions, the ferromagnetic material of the present disclosure may provide heating power of at least an order of magnitude greater than current materials used for magnetic heating.

[0009] The magnetic heating system and method may be configured to provide medical treatment. For example, the magnetic material may be provided in an implant and/or in the form of nanoparticles, and may be located, by injection or other implantation procedure, within a human or animal body. Using the magnetic field generator, heat output from the magnetic material can be controlled remotely, from a position external to the body. In some embodiments, the heat is used to provide a therapeutic effect.

[0010] The system and method may be adapted to provide hyperthermia therapy, which can be used to treat cancer. The ferromagnetic material can be injected into or implanted in or adjacent a tumour. The surrounding tumour tissue is heated by the ferromagnetic material, killing tumour cells without substantial damage to healthy tissue.

[0011] For the purposes of hyperthermia therapy or otherwise, the magnetic material may be adapted to provide for heating above body temperature. Heating cancer cells to a temperature above body temperature, e.g. a temperature greater than 40°C, can cause cell damage or apoptosis. The temperature to which tissue or other mediums are heated can be substantially dependent on the Curie temperature of the ferromagnetic material. The Curie temperature of the ferromagnetic material may therefore be selected to be greater than 40°C. Nevertheless,

depending on the intended purpose of the heating, whether for medical treatment or otherwise, the ferromagnetic material may be selected to have one of a variety of different Curie Temperatures. For example, the Curie Temperature may be between 20 and 80°C, 40 and 60°C, 40 and 50°C or otherwise. In one embodiment of the present disclosure, the Curie temperature of the ferromagnetic material is 46.1°C.

[0012] Embodiments of the present disclosure are not necessarily limited to medical use. They can have applications in any field where remote heating is desirable. As one example, they may be used in heat assisted forward osmosis water desalination technology.

[0013] Particularly, although not necessarily exclusively, for the purpose of medical treatment, the magnetic field generator can be adapted to apply an alternating magnetic field having an effective field strength in the order of 10^9 A/(ms). For example, the magnetic field generator may be adapted to apply an alternating magnetic field having an effective field strength of from about 4.85×10^8 A/(ms) to about 5×10^9 A/(ms).

[0014] The substantially high heating power of the ferromagnetic material can mean medical treatment is less invasive, since lower applied magnetic field strength may be required to achieve a desired heating effect.

[0015] In one aspect of the present disclosure there is provided an injectable composition comprising ferromagnetic material exhibiting a first-order magnetic transition.

[0016] In another aspect of the present disclosure there is provided an implant comprising ferromagnetic material exhibiting a first-order magnetic transition.

[0017] In yet another aspect of the present disclosure there is provided use of a ferromagnetic material exhibiting a first-order magnetic transition in a method of medical treatment.

[0018] In yet another aspect of the present disclosure there is provided use of a ferromagnetic material exhibiting a first-order magnetic transition in a heat assisted forward osmosis water desalination process.

[0019] In aspects of the present disclosure, any ferromagnetic material that exhibits a first-order magnetic transition, and which can undergo magnetic transition at a temperature similar to a temperature at which heating is desired, may be used. The ferromagnetic material may be a La-Fe-Si based material. The ferromagnetic material may be a compound having the formula $\text{La}(\text{Fe},\text{Si})_{13}$. As an alternative example, the ferromagnetic material may be a Mn-Fe-P based material. The ferromagnetic material may be a compound having the formula $\text{MnFe}_{1-x}\text{Co}_x\text{P}_{1-y}\text{Ge}_y$. As a further example, the ferromagnetic material may be a Mn-As-Sb based material. The ferromagnetic material may be a compound having the formula $\text{MnAs}_{1-x}\text{Sb}_x$.

[0020] A hydrogenation or dehydrogenation process may be used to tune the Curie temperature. Using La-Fe-Si based material as an example, the ferromagnetic material may therefore be a hydrided compound having the formula $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_y$. To achieve desired heating levels for therapeutic purposes, y may be between 1.4 and 2.4, between 1.6 and 2.0, equal to or above 1.7, between 1.7 and 2.0, between 1.7 and 1.9, between 1.7 and 1.8 or about 1.75, for example.

[0021] According to one aspect of the disclosure, there is provided a compound of the formula $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_y$ where y is equal to or greater than 1.7.

[0022] According to one aspect of the disclosure, there is provided a compound of the formula $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$.

[0023] In one embodiment, a compound of the formula $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ exhibits a curie temperature of 46.1°C , which may be particularly suitable for hyperthermia therapy, for example.

[0024] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Brief Description of Drawings

[0025] By way of example only, embodiments are now described with reference to the accompanying drawings, in which:

[0026] Fig. 1 shows the relationship between the magnetic polarisation (M) of a ferromagnetic material and a statically applied magnetic field (H);

[0027] Fig. 2 shows temperature dependence of spontaneous magnetisation of second-order ferromagnetic material and represents the mechanism of self-controlled heating;

[0028] Fig. 3 shows temperature dependence of spontaneous magnetisation of first-order ferromagnetic material and represents the mechanism of self-controlled heating;

[0029] Fig. 4 shows static hysteresis loss for a first-order ferromagnetic material over temperature, and also magnetisation of the first-order ferromagnetic material over temperatures (inset);

[0030] Fig. 5 shows temperature over time of water containing pulverised first-order ferromagnetic material under an applied alternating magnetic field;

[0031] Fig. 6 shows specific heat absorption rates of different magnetic samples at different magnetic field strengths;

[0032] Fig. 7a shows temperature dependence of magnetisation for T_C -tuned $\text{La}(\text{Fe},\text{Si})_{13}$ compounds and Fig. 7b shows the relationship between the Curie temperature and the hydrogen concentration (y) for $\text{LaFe}_{11.57}\text{Si}_{1.43}\text{H}_y$.

[0033] Figs. 8a and 8b illustrate a heating system configured to provide hyperthermia therapy according to an embodiment of the present disclosure;

[0034] Figs. 9a and 9b illustrate a heating system configured to provide hyperthermia therapy according to another embodiment of the present disclosure; and

[0035] Fig. 10 shows a relationship between the magnetic polarisation (M) of first order ferromagnetic material and a statically applied magnetic field (H) at various different measurement temperatures.

Description of Embodiments

[0036] Ferromagnetic materials exhibiting a first-order magnetic transition have a large isothermal entropy change (ΔS) or adiabatic temperature change induced by a pseudo-static magnetic field. This is known as the magnetocaloric effect. The inventors have determined that these materials can be particularly useful in heating applications, and irreversible heating power of these materials can be enhanced dramatically by exposure to alternating magnetic fields. These ferromagnetic materials can be particularly advantageous for use in medical treatment, such as hyperthermia treatment, although they can have applications in other fields where heating is desired, such as a heat assisted forward osmosis water desalination technology.

[0037] A ferromagnetic material with a first-order magnetic transition (T_C), undergoes an anomalous increase near the transition temperature. It has been found that hysteresis loss can be enhanced by 800% through use of first-order ferromagnetic materials, over a narrow temperature range (e.g., 2 to 3 K) immediately below T_C . Since the transition temperature of the ferromagnetic material can be tuneable over a wide temperature range that includes human body temperature, the unique hysteresis loss enhancement at the first-order magnetic transition can result in a very abrupt increase in the magnetic heating power at an ideal therapeutic temperature, e.g. an ideal temperature for hyperthermia treatment. The heating effect is self-regulated by the Curie temperature under an alternating magnetic field, leading to a new approach to magnetic heating in applications such as hyperthermia therapy for cancer treatment.

[0038] To aid understanding of embodiments of present disclosure, heating mechanisms of certain magnetic materials are now described.

[0039] Fig. 1 shows schematically the relationship between the magnetic polarisation (M) of a ferromagnetic material and a statically applied magnetic field (H). The magnetic polarisation shows a tendency to increase with increasing applied magnetic field; however, the M value is saturated at $H = H_a$, the anisotropy field. The reverse magnetic field to depolarise the magnetisation from M_s to zero is defined by the coercivity (H_c). The coercivity is known to be highly dependent on the grain size in the nanoscale regime because the magnetic correlation length of materials is usually between 10 and 100 nm. The energy loss associated with the static magnetic polarisation process in a ferromagnetic (ΔE) is given by the area inside the $\mu_0 M$ - H loop, i.e.:

$$\Delta E = \mu_0 f H dM, \quad \text{Equation 1}$$

where μ_0 is the permeability of free space.

[0040] When the maximum magnetic field applied is lower than H_k (as illustrated by the minor loops in Fig. 1), the magnetisation curve becomes unsaturated and thus, the coercive field is smaller than H_c , leading to a smaller area inside the $\mu_0 M$ - H loop as compared with the saturated loop. The energy loss per unit time (P) under an alternating magnetic field is given by the area inside the loop (ΔE) multiplied by the frequency ($\Delta E \cdot f$) and this corresponds to the heating power.

[0041] The effect of the maximum external magnetic field on the area inside the hysteresis curve explains the field dependence of the heating power. Fig. 1 indicates that a large ΔE value is obtained by choosing a material with large M_s and H_c values while tuning the external field to H_k . The maximum magnetic field allowed in hyperthermia may be capped by the condition $H \cdot f \sim 10^9$ A/(ms), where the product of the applied field H and frequency f is the effective magnetic field. Hence, the ideal H_k value for the maximum heating power depends on the frequency.

[0042] The heating mechanism of superparamagnetic nanoparticles, however, is quite different from that of ferromagnetic materials. The M - H curve of materials in a superparamagnetic state is known to follow the Langevin function and the field dependence of the magnetic polarisation is fully reversible. Thus, unlike ferromagnetic materials, the M - H curve of a superparamagnetic material does not exhibit any hysteresis behaviour under a static magnetisation process. The primary cause of the heating effect in superparamagnetic particles is the relaxation behaviour of the magnetisation direction in particles which results in a certain phase shift between the alternating $H(t)$ and $\mu_0 M(t)$ signals.

[0043] In contrast to each of the above-described techniques, embodiments of the present disclosure utilise a ferromagnetic material to which an alternating magnetic field is applied. While a loss mechanism as described above with reference to Fig. 1 is therefore applicable, it is not the only loss mechanism. Since magnetisation polarisation is induced by the change in the magnetic domain configurations which is time dependent, the response of the magnetic polarisation to external alternating magnetic field shows a finite time delay due to the domain

relaxation process. This delay causes a certain phase shift between $H(t)$ and $\mu_0 M(t)$ which can be described by a complex magnetic permeability; the power loss is related to the imaginary part of the permeability. Hence, the area inside the M - H loop under an alternating magnetic field is far larger than under a static field. This effect is significant at high frequencies and the power loss per cycle can be enhanced by 2 orders of magnitude in the kHz range in some soft magnetic materials, for example. Heating power of magnetic materials may therefore be enhanced dramatically by increasing the driving frequency.

[0044] The use of ferromagnetic materials allow for self-controlled heating. In particular, in addition to the potential for large heating power, ferromagnetic materials can self-regulate heating power closer to the Curie temperature (T_C). This offers a considerable advantage over heating by superparamagnetic particles with which the temperature is controlled by adjusting the applied field strength.

[0045] The mechanism of self-controlled heating in conventional second-order ferromagnetic material is represented in Fig. 2, in which the temperature dependence of the spontaneous magnetisation of the ferromagnetic material is shown schematically. The spontaneous magnetisation (M_s) is given by the vector sum of the atomic magnetic moment (m), $M_s = \sum_i \vec{m}_i$.

[0046] Although the atomic magnetic moments are strongly correlated at low temperature, via the positive exchange interaction, and the vector sum M_s is large, the spontaneous magnetisation shows negative temperature dependence because of the thermal vibration at higher temperatures. The effect of the exchange interaction is lost completely at the Curie temperature (T_C) and the atomic magnetic moments above T_C are oriented at random, resulting in zero M_s . Consequently, the hysteresis loss of ferromagnetic particles defined by Equation 1 is lost at $T = T_C$ and the heating power is switched off at T_C . Naturally, the heating power recovers when the particles are cooled below T_C . Since T_C of ferromagnetic materials can be adjusted to a therapeutic temperature, this process can be particularly helpful in heating systems, e.g., where the material may be implanted in a subject for medical treatment, such as hyperthermia treatment.

[0047] The present disclosure further recognises, however, that magnetic heating mechanisms with larger heating power can be realised at desired temperatures, e.g. therapeutic temperatures, by using material exhibiting a first-order magnetic transition.

[0048] The temperature dependence of M_s in ferromagnetic materials with a second-order magnetic transition is described well by mean field theory and the normalised temperature dependence, *i.e.* $M_s(T)/M_s(0)$ versus T/T_C of ferromagnetic materials is described universally by the Brillouin function which gives a gradual decrease in M_s near T_C . Given the fact that the difference between the body temperature and the therapeutic temperature (e.g., 43 - 47 °C) is relatively small, M_s , and thus the heating power of ferromagnetic materials having their T_C at the therapeutic temperature, is already quite limited at body temperature. This is the major limiting factor in the self-controlled heating by ferromagnetic materials.

[0049] The problem of the suppressed M_s value at body temperature remains when a variety of different ferromagnets are used, due to their temperature dependence following the Brillouin function.

[0050] However, ferromagnetic materials according to the present disclosure, exhibiting first-order magnetic transition, have a temperature dependence for M_s near T_C that does not follow the Brillouin function. One example of such ferromagnetic material according to the present disclosure is a $\text{La}(\text{Fe},\text{Si})_{13}$ compound.

[0051] Fig. 3 shows schematically the temperature dependence of M_s for a ferromagnetic material with the first-order magnetic transition at T_C . Unlike the second-order magnetic transition at T_C represented in Fig. 2, where the ferromagnetic order of spins diminishes cooperatively at a critical temperature, both ferromagnetic and paramagnetic phases may coexist in the 1st order materials near T_C (Fig. 3) and the abrupt decrease of M_s is governed by the nucleation-and-growth process of the paramagnetic phase in the ferromagnetic matrix rather than the molecular field in the ferromagnetic phase. Hence, the decrease in the spontaneous magnetisation near T_C can be very abrupt. $\text{La}(\text{Fe},\text{Si})_{13}$ has a very steep change of M_s due to the presence of such a first-order magnetic transition.

[0052] Through creative research, the present inventors have become aware that ferromagnetic materials exhibiting first-order magnetic transition have been used in magnetic

refrigeration applications, which is a considerably different application and field of technology to embodiments described herein. The refrigeration process relies on static magnetic fields to ensure adequate heat exchange, and takes advantage of the step change of the magnetic enthalpy of the ferromagnetic material in an applied magnetic field that can induce a sudden cooling of the material near the magnetic transition.

[0053] However, the present inventors have determined that ferromagnetic materials exhibiting first-order magnetic transition can offer considerable advantages as a medium for self-controlled isothermal heating, e.g. for use in medical treatment, and have determined that considerable benefits can be achieved through the application of an alternating magnetic field to the ferromagnetic material to induce heating.

[0054] According to an embodiment of the present disclosure, a melt-spun La-Fe-Si based sample was prepared and tuned by hydrogenation such that it had a T_C value of 46.1°C. (The La-Fe-Si compound had the formula $\text{LaFe}_{11.57}\text{Si}_{1.43}\text{H}_{1.75}$ in this instance.) T_C of 46.1°C was calculated through measurement of magnetisation over a range of temperatures, as shown in the inset of Fig. 4.

[0055] M - H curves of $\text{LaFe}_{11.57}\text{Si}_{1.43}\text{H}_{1.75}$, acquired upon heating at a rate of 1.6×10^{-3} K/s, at different measurement temperatures, are shown in Fig. 10. The 1st order magnetic transition is reflected in the shape of the M - H curves. The M - H curves well below T_C (46.1°C) show little irreversibility whereas the irreversibility is pronounced considerably between 42 and 46 °C, immediately below T_C . However, no appreciable increase in the coercivity is evident on the M - H curves at these temperatures, indicating that this hysteretic behavior is unrelated to conventional magnetic hardening caused by the magnetic anisotropy. Rather, this enhanced irreversibility near T_C is attributable to the phase coexistence where the ferromagnetic phase is induced in a matrix of the paramagnetic phase by an external magnetic field. The nucleation-and-growth process associated with the magnetic phase transition usually requires stress accommodation, adding an extra irreversibility to the Curie transition. Although this irreversibility on the M - H curve is often problematic when this compound is applied for magnetic refrigeration, this very effect due to the 1st order transition is ideal for enhancing the loss power in the vicinity of T_C .

[0056] Fig. 4 also shows the static hysteresis loss for the ferromagnetic material, over a temperature measurement range including and extending beyond the range shown in Fig. 10. As can be seen over the wider temperature range, the hysteresis loss shows a tendency to decrease gradually as temperature increases towards T_C because both the spontaneous magnetisation and the intrinsic coercivity normally have negative temperature dependence. However, the hysteresis loss of the sample exhibited an increase in a temperature range of between 42 and 46°C as indicated above and a particularly dramatic increase (by about 800 %) in a very narrow temperature range of between 44 and 46°C. This anomalous behaviour had not previously been recognised and the inventors recognised that the dramatic increase of the hysteresis loss indicated that the heating power of this first-order ferromagnetic material could be even greater under the application of alternating magnetic field, in consideration of higher dynamic loss that would be induced.

[0057] Heating power of the sample was subsequently analysed. The temperature of water containing the sample, in a pulverised form at a concentration of 10 mg/cc, was measured under an applied alternating magnetic field of 56 Oe (4.5 kA/m) at 279 kHz, [$H \cdot f = 1.25 \times 10^9$ A/(ms)] using an infrared thermometer. The results are presented in Fig. 5. Results for commercially available magnetite (Fe_3O_4) powders suspended in water with the same concentration are also shown in Fig. 5 for comparison.

[0058] The speed of increase of the temperature of the T_C -tuned $\text{La}(\text{Fe},\text{Si})_{13}$ -containing water or the $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ -containing water was dramatic between room temperature and the therapeutic temperature range, the increase taking about one minute. In contrast, for the same time period, the magnetite provided a temperature increase of less than 1°C. The results highlighted the significantly greater heating effect caused by the “first-order” ferromagnetic sample. Despite the dramatic initial heating power using this type of sample, water temperature remained well-regulated thereafter due to the switching effect at the fine-tuned T_C .

[0059] Specific heat absorption rates of the $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ sample were calculated at different magnetic fields and compared with conventional magnetic samples types. The results are shown in Table 1 below and represented graphically in Fig. 6. As can be seen, the $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ sample had a specific heat absorption rate that was an order of magnitude higher than the conventional magnetic materials

Table 1

Implant	H (kA/m) Hall Prob	Frequency f (kHz)	Hf ($\times 10^8$)	Concentration (mg/ml)	SAR (W/gr)
$\text{LaFe}_{11.57}\text{Si}_{1.43}\text{-H}_{1.75}^*$	3	279	9	10	64.2
$\text{LaFe}_{11.57}\text{Si}_{1.43}\text{-H}_{1.75}^*$	4.5	279	12.5	10	231.8
$\text{LaFe}_{11.57}\text{Si}_{1.43}\text{-H}_{1.75}^*$	8.8	279	25	10	521.5
$\text{LaFe}_{11.57}\text{Si}_{1.43}\text{-H}_{1.75}^*$	17.7	279	50	10	543.1
$\text{MgFe}_2\text{O}_4^{**}$	3	279	9	10	3.4
$\text{MgFe}_2\text{O}_4^{**}$	4.5	279	12.5	10	6.7
$\text{MgFe}_2\text{O}_4^{**}$	8.8	279	25	10	19.6
$\text{MgFe}_2\text{O}_4^{**}$	17.7	279	50	10	37.7
$\text{Fe}_3\text{O}_4^{***}$	4.5	279	12.5	10	1.3
$\text{Fe}_3\text{O}_4^{***}$	8.8	279	25	10	10.7

* $\text{LaFe}_{11.57}\text{Si}_{1.43}\text{-H}_{1.75}$: ribbons prepared by melt spinning process

** MgFe_2O_4 : Magnesium ferrite nanoparticles prepared by ultrasonic assisted co-precipitation method

*** Fe_3O_4 : Magnetite nanoparticles, Sigma Aldrich - 637106 - Iron oxide (ii,iii) nanopowder, <50 nm particle size (TEM), $\geq 98\%$ trace metals basis

[0060] While $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ with a T_C of 46.1 °C has been discussed above, this T_C value being considered as potentially ideal for hyperthermia therapy application, in other embodiments $\text{La}(\text{Fe},\text{Si})_{13}\text{H}_{1.75}$ with different ratios of Fe and Si and/or with different T_C may be used, e.g. depending on the desired heating temperatures (e.g. the desired therapeutic temperatures) or otherwise.

[0061] The temperature dependence of magnetization for T_C -tuned hydrided $\text{La}(\text{Fe},\text{Si})_{13}$ compounds was analysed and the results are presented in Fig. 7a. The values of T_C determined for these compounds were 350 K, 319 K, 252 K and 204 K. The relationship between the Curie temperature and the hydrogen concentration (y) for $\text{LaFe}_{11.57}\text{Si}_{1.43}\text{H}_y$ is shown in Fig. 7b. Some literature values reported by *Lyubina et al.* (Journal of Magnetism and Magnetic Materials vol. 320 (2008) pp. 2252–2258) are also included in the plots for comparison. T_C for $\text{La}(\text{Fe},\text{Si})_{13}$ was found to be readily tunable between 200 K (-73 °C) and

350 K (77 °C) by controlling the hydrogen content. Thus, depending on the application, a Curie temperature may be selected that falls within a variety of different ranges. As examples only, the selected T_C may be between 20 and 80°C, 40 and 60°C, 40 and 50°C or otherwise. As examples only, y may be between 1.4 and 2.4, between 1.6 and 2.0, equal to or above 1.7, between 1.7 and 2.0, between 1.7 and 1.9, between 1.7 and 1.8 or about 1.75.

[0062] Other ferromagnetic compounds that are not based on La-Si-Fe, but which also exhibit a first-order magnetic transition, may be employed in embodiments of the present disclosure. The ferromagnetic material may be a Mn-Fe-P based material, for example, having the formula $\text{MnFe}_{1-x}\text{Co}_x\text{P}_{1-y}\text{Ge}_y$. As another example, the ferromagnetic material may be a Mn-As-Sb based material having the formula $\text{MnAs}_{1-x}\text{Sb}_x$. These first-order ferromagnetic materials have T_C in the ranges extending from about 176K to 323K in the case of $\text{MnFe}_{1-x}\text{Co}_x\text{P}_{1-y}\text{Ge}_y$ (*E. Bruck et al.*, ScriptaMaterialia 67 (2012) 590–593) and from about 280 K to 320 K in the case of $\text{MnAs}_{1-x}\text{Sb}_x$ (*H. Wada, Y. Tanabe*, Appl. Phys. Lett. 2001, 79, 3302). These temperature ranges are considered suitable for a variety of different applications including hyperthermia therapy, for example.

[0063] A heating system configured to provide hyperthermia therapy according to an embodiment of the present disclosure is illustrated in Figs. 8a and 8b. The heating system includes ferromagnetic material 1 exhibiting a first-order magnetic transition and having a Curie temperature of between 40 and 50°C, the ferromagnetic material being provided in nanoparticulate form. Referring to Fig. 8a, the nanoparticles 1 are injected using a syringe 6 into a cancerous tumour 2 of a subject 3. Subsequently, and with reference to Fig. 8b, a magnetic field generator 4 is arranged to apply an alternating magnetic field 5 from a remote location to the ferromagnetic material inside the tumour 2, causing apoptosis of the cancerous cells.

[0064] A heating system according to another embodiment of the present disclosure is illustrated in Figs. 9a and 9b. The heating system includes ferromagnetic material 10 exhibiting a first-order magnetic transition and having a Curie temperature of between 40 and 50°C, the ferromagnetic material being provided in the form of an implant. Referring to Fig. 9a, the ferromagnetic implant 10 is surgically implanted into a cancerous tumour 20 of a subject 30. Subsequently, referring to Fig. 9b, a magnetic field generator 40 is arranged to

apply an alternating magnetic field 50 from a remote location to the ferromagnetic material inside the tumour 20, causing apoptosis of the cancerous cells.

[0065] In alternative embodiments, the ferromagnetic material may be employed for remote heating in other technologies. In a heat assisted forward osmosis water desalination process, for example, magnetic field-induced heating can be used to recover water from swollen hydrogel draw agents. In *Razmjou et al.* (Environ. Sci. Technol. 2013, 47, 6297–6305) fast deswelling of polymer hydrogel particles was achieved by incorporating magnetic $\gamma\text{-Fe}_2\text{O}_3$ nanoparticles exhibiting a second-order magnetic transition. The technique described in *Razmjou et al.*, which is incorporated by reference herein, may be further enhanced through use of ferromagnetic materials exhibiting a first-order transition as disclosed herein.

[0066] It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the above-described embodiments, without departing from the broad general scope of the present disclosure. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

CLAIMS:

1. A magnetic heating system comprising:
ferromagnetic material exhibiting a first order magnetic transition; and
a magnetic field generator adapted to apply an alternating magnetic field to the ferromagnetic material to induce heat emission from the ferromagnetic material.
2. The system of claim 1, wherein the ferromagnetic material has a Curie temperature T_C of between 20 and 80°C.
3. The system of claim 1, wherein the ferromagnetic material has a Curie temperature T_C of between 40 and 50°C.
4. The system of claim 1, wherein the ferromagnetic material has a Curie temperature T_C of about 46°C.
5. The system of any one of the preceding claims, wherein the ferromagnetic material comprises $\text{La}(\text{Fe}, \text{Si})_{13}$.
6. The system of any one of the preceding claims, wherein the ferromagnetic material comprises hydrided $\text{La}(\text{Fe}, \text{Si})_{13}$ having the formula $\text{La}(\text{Fe}, \text{Si})_{13}\text{H}_y$.
7. The system of claim 6, wherein y is between 1.4 and 2.4.
8. The system of claim 7, wherein y is between 1.7 and 1.8.
9. The system of claim 8, wherein y is about 1.75.
10. The system of any one of the preceding claims, wherein the magnetic field generator is adapted to apply an alternating magnetic field having an effective field strength in the order of 10^9 A/(ms).

11. The system of any one of the preceding claims, wherein the magnetic field generator is adapted to apply an alternating magnetic field having an effective field strength of between about 4.85×10^8 A/(ms) and 5×10^9 A/(ms).
12. The system of any one of the preceding claims, wherein the system is adapted to provide medical treatment.
13. The system of claim 12, wherein the system is adapted to provide hyperthermia therapy.
14. The system of claim 12 or 13, comprising an implant adapted to be implanted in a human or animal body, the implant comprising the ferromagnetic material.
15. The system of claim 12 or 13, comprising nanoparticles adapted to be implanted in a human or animal body, the nanoparticles comprising the ferromagnetic material.
16. The system of claim 12 or 13, comprising an injectable composition, the injectable composition comprising the ferromagnetic material.
17. The system of any one of claims 1 to 11, wherein the system is adapted to be used in a heat assisted forward osmosis water desalination process
18. A method of heating comprising:
applying an alternating magnetic field to a ferromagnetic material to induce heat emission from the ferromagnetic material, wherein the ferromagnetic material exhibits a first order magnetic transition.
19. The method of claim 18, wherein the ferromagnetic material has a Curie temperature T_C of between 20 and 80°C.
20. The method of claim 18, wherein the ferromagnetic material has a Curie temperature T_C of between 40 and 50°C.

21. The method of claim 18, wherein the ferromagnetic material has a Curie temperature T_C of about 46°C.
22. The method of any one of claims 18 to 21, wherein the ferromagnetic material comprises La(Fe,Si)_{13} .
23. The method of any one of claims 18 to 22, wherein the ferromagnetic material comprises hydrided La(Fe,Si)_{13} having the formula $\text{La(Fe,Si)}_{13}\text{H}_y$.
24. The method of claim 23, wherein y is between 1.4 and 2.4.
25. The method of claim 23, wherein y is between 1.7 and 1.8.
26. The method of claim 23, wherein y is about 1.75.
27. The method of any one of claims 18 to 26, wherein the applied alternating magnetic field has an effective field strength in the order of 10^9 A/(ms).
28. The method of claim 27, wherein the applied alternating magnetic field has an effective field strength of between about 4.85×10^8 A/(ms) and 5×10^9 A/(ms).
29. The method of any one of claims 18 to 28 wherein the method is a method of medical treatment.
30. The method of claim 29, wherein the method of medical treatment is hyperthermia therapy.
31. The method of any one of claims 18 to 30 comprising implanting the ferromagnetic material in a human or animal body.
32. The method of any one of claims 18 to 30 comprising injecting the ferromagnetic material in a human or animal body.

33. Use of ferromagnetic material exhibiting a first order magnetic transition in a method of medical treatment.
34. The use of claim 33, wherein the method of medical treatment comprises hyperthermia therapy.
35. The use of claim 33 or 34, wherein the ferromagnetic material has a Curie temperature T_C of between 20 and 80°C.
36. The use of claim 33 or 34, wherein the ferromagnetic material has a Curie temperature T_C of between 44 and 48°C.
37. The use of claim 33 or 34, wherein the ferromagnetic material has a Curie temperature T_C of about 46°C.
38. The use of any one of claims 33 to 37, wherein the ferromagnetic material comprises La(Fe,Si)_{13} .
39. The use of any one of claims 33 to 38, wherein the ferromagnetic material comprises hydrided La(Fe,Si)_{13} having the formula $\text{La(Fe,Si)}_{13}\text{H}_y$.
40. The use of claim 39, wherein y is between 1.4 and 2.4.
41. The use of claim 39 wherein y is between 1.7 and 1.8.
42. The use of claim 39, wherein y is about 1.75.
43. A compound of the formula $\text{La(Fe,Si)}_{13}\text{H}_y$, where y is equal to or above 1.7.
44. A compound according to claim 43, wherein y is between 1.7 and 1.8.
45. A compound of the formula $\text{La(Fe,Si)}_{13}\text{H}_{1.75}$.

46. An injectable composition comprising ferromagnetic material exhibiting a first order magnetic transition.

47. A medical implant comprising ferromagnetic material exhibiting a first order magnetic transition.

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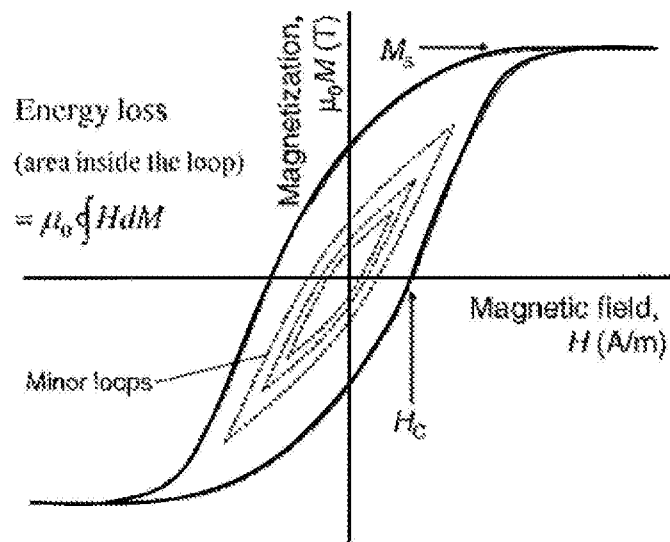


Fig. 1

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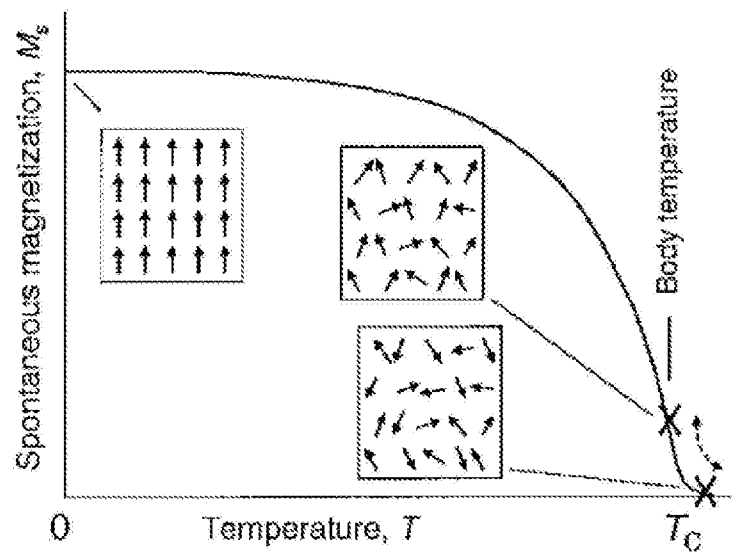


Fig. 2

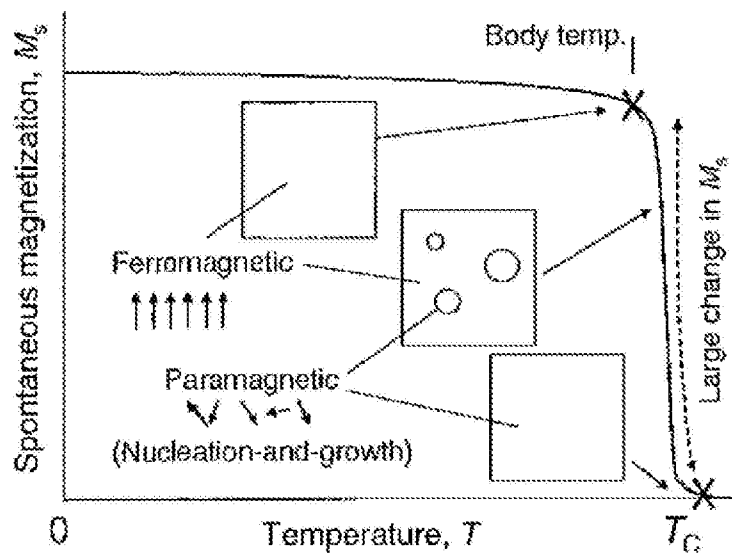


Fig. 3

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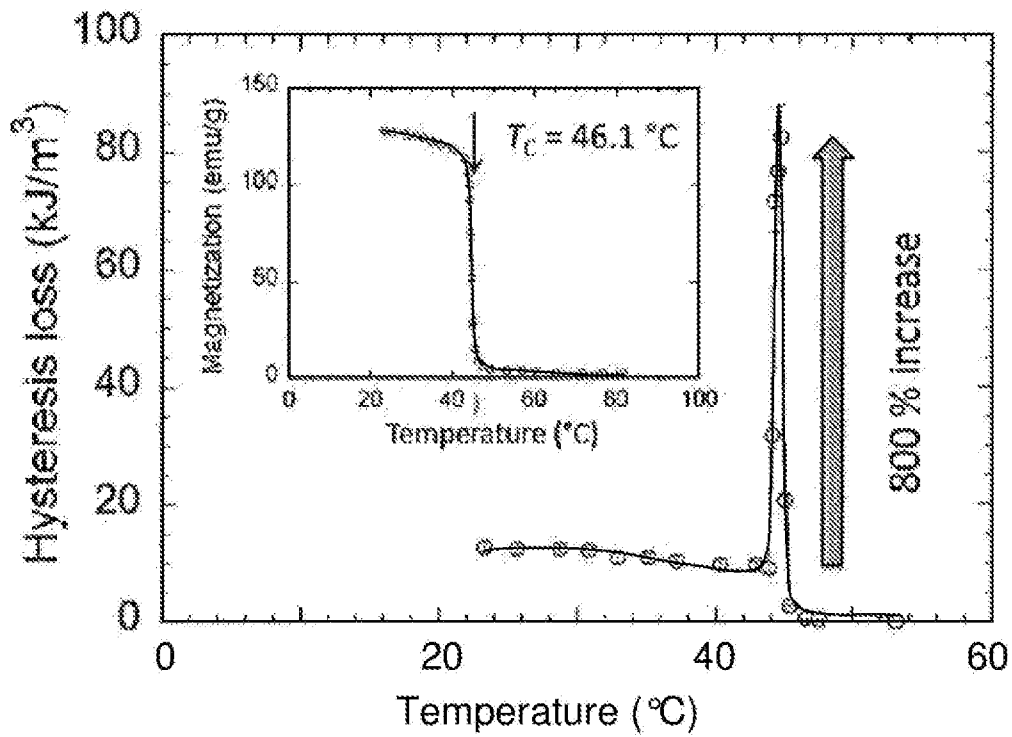


Fig. 4

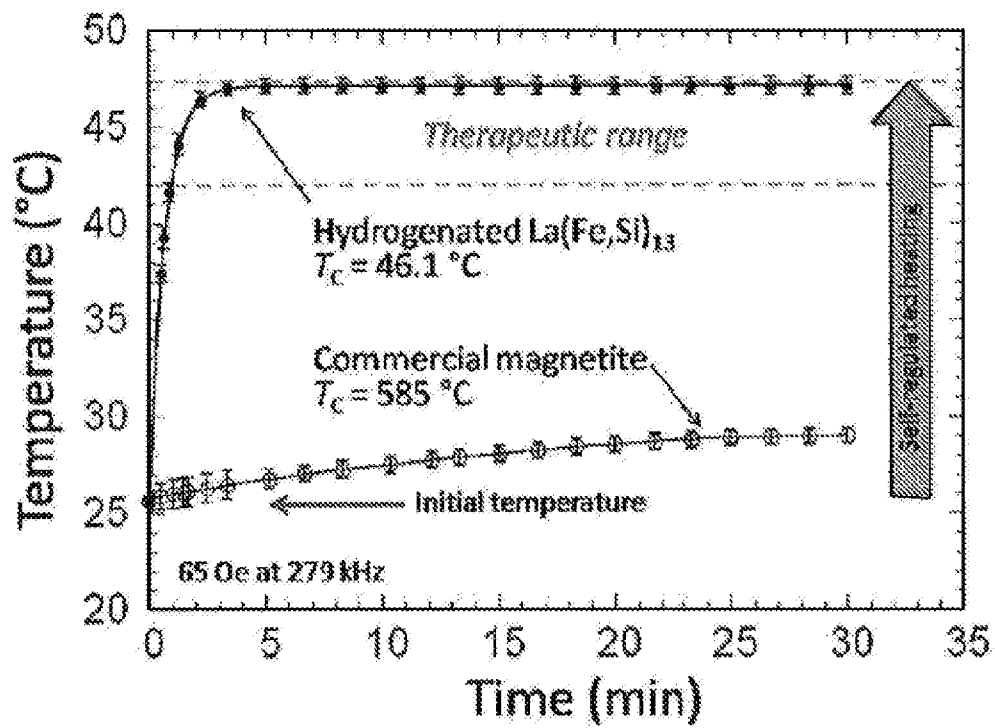


Fig. 5

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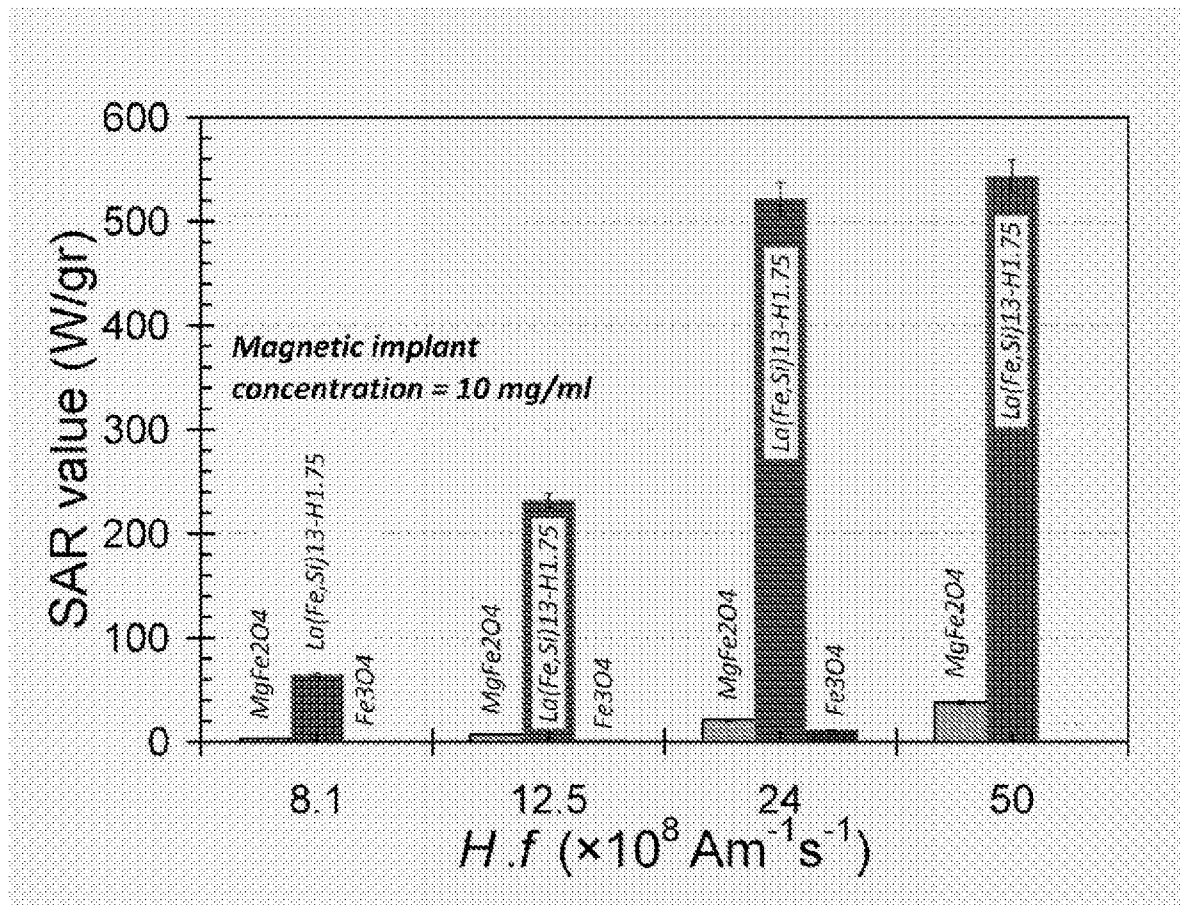


Fig. 6

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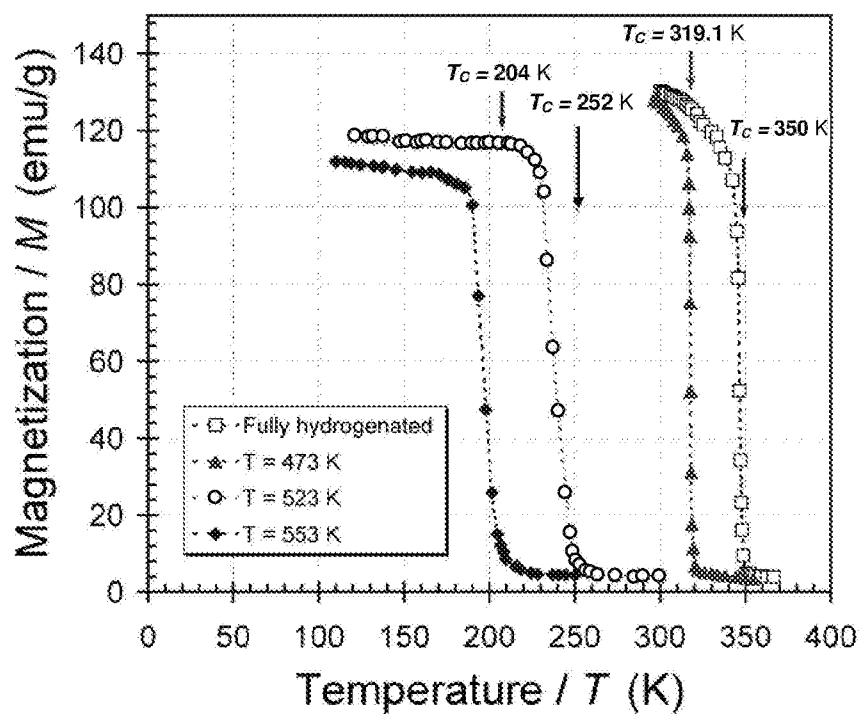


Fig. 7a

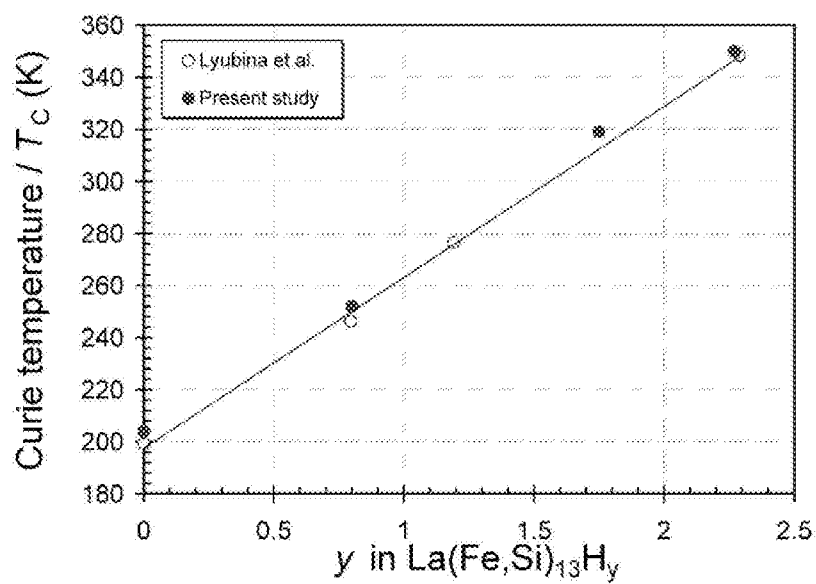


Fig. 7b

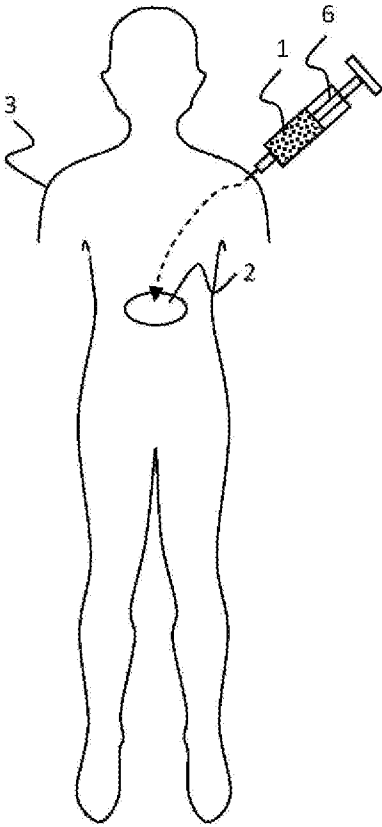


Fig. 8a

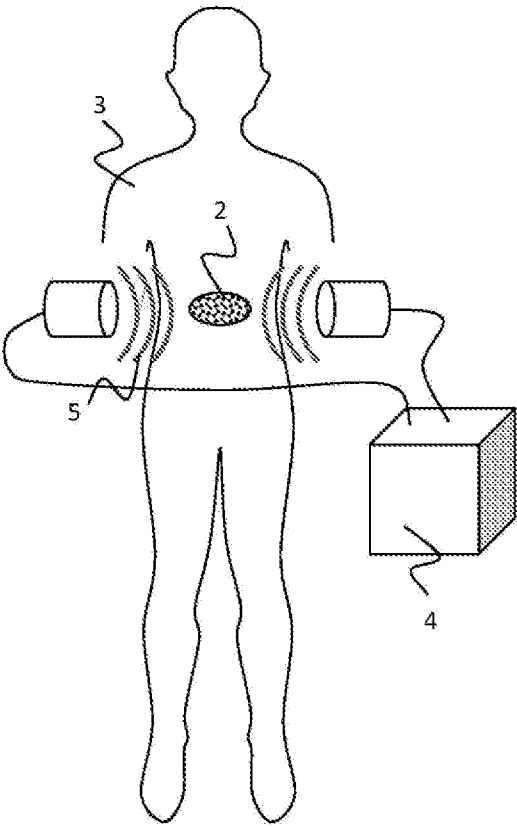
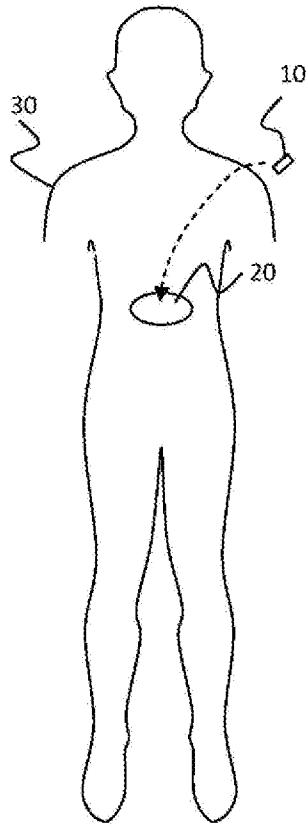
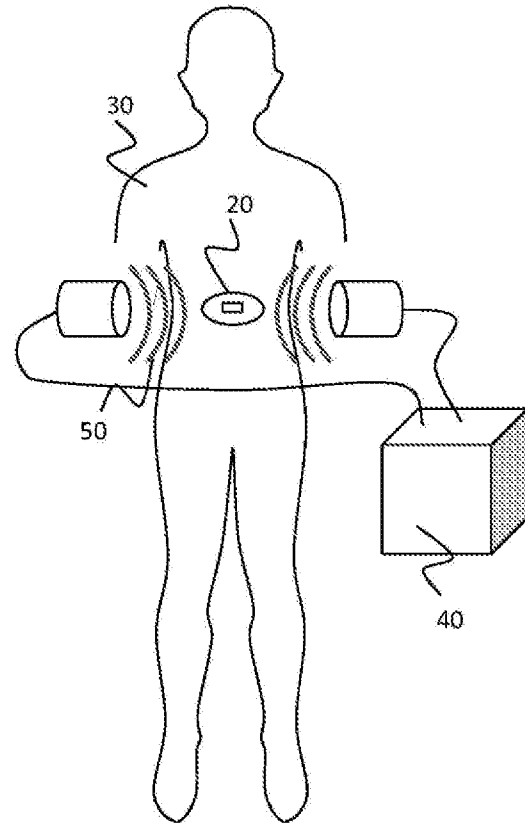
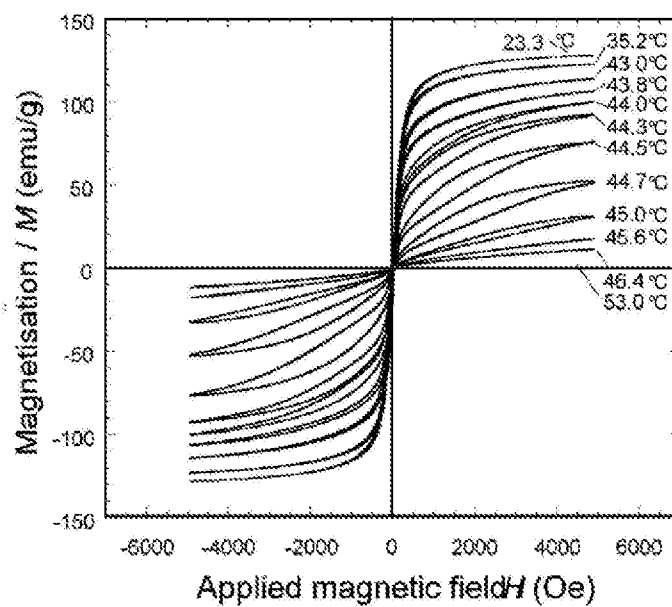


Fig. 8b

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Fig. 9aFig. 9b

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**Fig. 10**

INTERNATIONAL SEARCH REPORT

 International application No.
PCT/AU2014/050423

A. CLASSIFICATION OF SUBJECT MATTER

A61N 2/10 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases: WPI, EPODOC, INSPEC and keywords: magnet, ferromagnet, heat, magnetic -field, La, Fe, Si and similar terms.

Esp@cenet:MONASH UNIVERSITY* and keywords: ferro*, heat*, magnet*, inventors name were also searched.

Google search and keywords: La(Fe, Si), therapy, therapeutic, magnetocaloric, heat, medical, medicine, cancer, tumor and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		
Date of the actual completion of the international search 3 March 2015		Date of mailing of the international search report 03 March 2015	
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au		Authorised officer Jayati Ray AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262223654	

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2014/050423
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/0070620 A1 (BRUECK) 24 March 2011 paragraphs 0004-0010, 0014-0026	1-42, 46-47
X	M. Krautz et al., "Reversible solid-state hydrogen-pump driven by magnetostructural transformation in the prototype system La(Fe,Si)13Hy", JOURNAL OF APPLIED PHYSICS, volume 112, 2012, pages 083918-1 to 083918-6. Results and Discussion part	43-45

Form PCT/ISA/210 (fifth sheet) (July 2009)

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2014/050423	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2011/0070620 A1	24 March 2011	US 8632814 B2	21 Jan 2014
		AU 2010297237 A1	03 May 2012
		CN 102714080 A	03 Oct 2012
		EP 2481061 A1	01 Aug 2012
		JP 2013505569 A	14 Feb 2013
		KR 20120070590 A	29 Jun 2012
		RU 2012115915 A	27 Oct 2013
		TW 201116285 A	16 May 2011
		US 2014093934 A1	03 Apr 2014
		WO 2011033084 A1	24 Mar 2011
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			