The Characteristics of Ferrite Cores with Low Curie Temperature and their Application

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Abstract—The utility of ferrite cores which have the Curie temperature in the vicinity of the room temperature and suddenly change the permeability vs. temperature characteristic near the Curie temperature is described in this paper.

Using the characteristics of these ferrite cores, the author made an overcurrent relay and a long delay circuit, and investigated their application to a temperature control device and to the thermomagnetic generator. These devices are smaller than usual, and operate with good accuracy.

The author finds that ferrite cores with low Curie temperature are materials important to the development of a new field in electrical engineering.

Introduction

By adding proper materials and through a process, ferrite cores with low Curie temperature have been obtained, whose permeability vs. temperature characteristics change sharply in the neighborhood of Curie temperature, in the case of the manufacture of Mn-Cu ferrite. The author, interested in the usefulness of such ferrite cores, has examined their magnetic characteristics and studied their application to the control and various other devices.

In the application of ferrite cores with low Curie temperature to electric devices, two principles hold. When heat input is given to ferrite cores, one principle explains why the permeability vs. temperature characteristics of ferrite cores change slowly in time, and the other explains their sudden change. The author made an overcurrent relay and a long delay circuit by making good use of the former principle, and investigated the application of the core to a temperature control device and to the thermomagnetic generator by using the latter principle. He succeeded in making these devices, which are smaller than usual, and which operate with good accuracy, because of the use of Curie temperature as a temperature reference. In this paper, he describes these results.

Basic Characteristics of Ferrite Cores

Generally, the Curie temperature of ferrite cores used for electric devices is in the region above 100°C or so. If proper treatment is given to the manufacture of Mn-Cu ferrite, the ferrite cores, which have the Curie temperature at any degree in the vicinity of room temperature, and whose permeability vs. temperature characteristic brings about a sudden change in the neighborhood of the Curie temperature, can be made.

Figure 1 shows the characteristics of permeability vs. temperature measured while exciting a frequency of 1 kc/s. When the ferrite cores with the previously mentioned characteristic are applied to various electric devices, a circuit, shown by Fig. 2(a), is generally used for detecting heat input signals in the form of electric output. Now let us observe the behavior of ferrite cores in this circuit. As shown in Fig. 3, the ferrite core is of a ring form. Assume that the Curie temperature of the core is represented by T_Q; the B-H curve, in which the temperature of the core does not reach the Curie temperature is shown by Fig. 3(b), and the relation between permeability and temperature of the core, by Fig. 3(c).

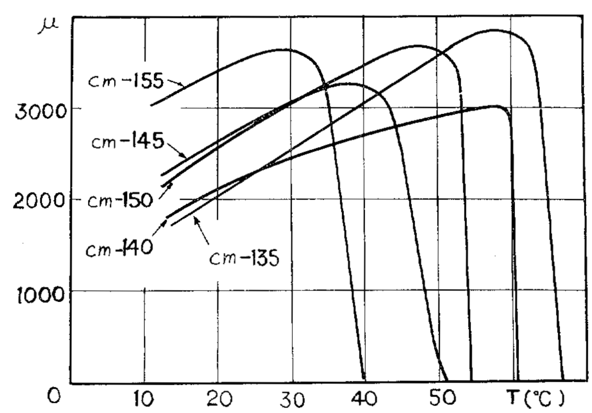

Fig. 1. Permeability vs. temperature curves of various specimen of ferrite core.

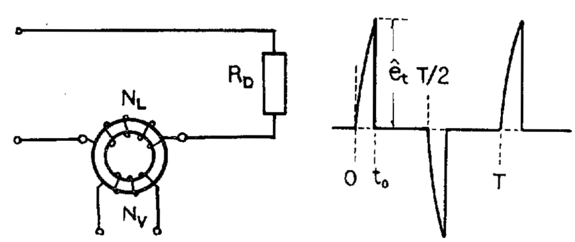

Fig. 2. Basic circuit and induced voltage waveshape.

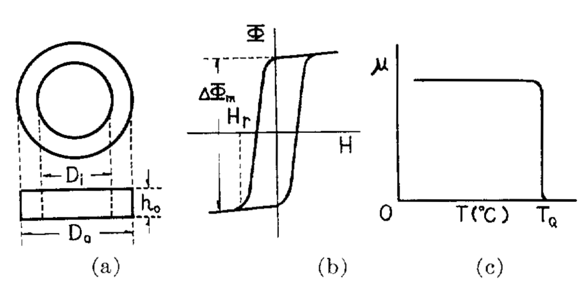

Fig. 3. Core construction and typical characteristics of ferrite core. (a) Ring core. (b) Hysteresis loop. (c) Idealized permeability vs. temperature curve.

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If, in the circuit of Fig. 2(a), the current of winding N_L is represented by I_L, the resistance of winding N_L by R_L, the hysteresis loss of ferrite core by W_c, the core temperature by T_n, the temperature in the circumference by T_o, and the heat transfer coefficient by h (which is assumed as constant in the region of the temperatures used in the experiment), the temperature of ferrite cores in the steady state is shown by the following relation:

$$T_n = (I^2{}_L\, R_L + W_c)/h + T_0. \tag{1}$$

In Fig. 3, the average diameter of the ferrite core is denoted by D_m, the magnetizing force of full control by H_r and the amount of the total flux $\Delta\Phi_m$. If the equivalent impedance of ferrite core is negligibly small in contrast to load resistance R_D, and if the temperature of magnetic core shown in (1) is smaller than the Curie temperature T_Q, the voltage of the waveshape shown by Fig. 2(b) will be induced at the terminal of winding N_v. Then $\hat{e}_t$ and t_0, shown in Fig. 2(b), are expressed by the following relation:

$$\hat{e}_t = [N_v \omega \Delta\Phi_m/(1 - \cos \omega t_o)] \sin \omega t_0. \tag{2}$$

$$t_0 = (1/\omega) \sin^{-1} (H_r D_m/0.4\, N_L \cdot \sqrt{2}\, I_L). \tag{3}$$

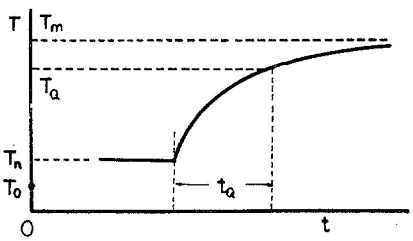

Fig. 4. Relationship of equation (4).

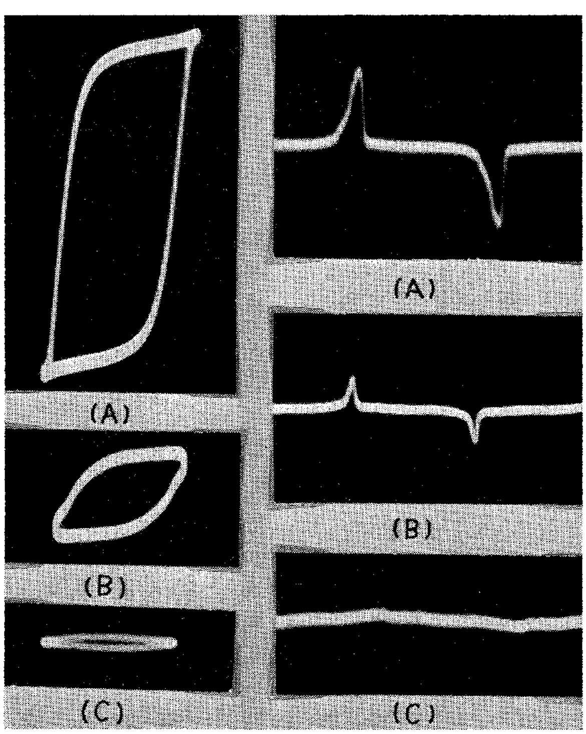

Fig. 5. Dynamic B-H loop and induced voltage waveshape affected by temperature. Temperature equals: (a) 35°C. (b) 38°C. (c) 39°C.

If the current in winding N_L, increases suddenly and continues at a constant value, and this value is represented by I_o, the temperature T, of the ferrite core will arise according to the following relation:

$$T = (T_m - T_n)\,[1 - e^{-\{I_0{}^2R_L + W_c/C_f(T_m - T_0)\}t}] + T_n. \tag{4}$$

T_m is the temperature of the magnetic core after infinite time. Figure 4 shows the relation of (4).

Now if $T_m > T_Q$ after time t_Q, the temperature of ferrite core arrives at the Curie temperature and the induced voltage of winding N_v becomes zero.

$$t_Q = (C_f/h) \log \{ [(I_0{}^2R_L + W_c)/h - (T_n - T_0)]/ [(I_0{}^2R_L + W_c)/h - (T_Q - T_0)]\}. \tag{5}$$

Figure 5 shows some examples of the dynamic B-H loop of ferrite core, at temperatures near the Curie temperature, and the induced voltage waveshapes of ferrite core. C_f is the heat capacity of ferrite core.

As is obvious from the above results, if the resistance R_L of winding N_L is fixed properly, the heat generated by R_L is used as input signal, and the temperature of the ferrite core arrived at the Curie temperature can be detected by the disappearance of the induced voltage of winding N_v. Now let us describe some examples of the practical application of this characteristic.

Application to Overcurrent Relay

As seen from (5), if the ferrite core shown in Fig. 1 is used, and R_L and C_f properly decided, a new inverse-time overcurrent relay can be made.

Figure 6 shows a circuit of the inverse-time overcurrent relay devised by the author. Let us explain its action by the use of Fig. 6. At first, the no-voltage release SW must be closed. If the load current flowing in the winding N_L is below the rated value (in case of a large load current, use a current transformer or a shunt resistor), the temperature of the ferrite core is below the Curie temperature, and the voltage of the waveshape shown in Fig. 2(b) appears across winding N_v. This voltage pulse is used to fire the silicon-controlled rectifiers (SCRs) and hence operates the no-voltage release to "on."

Under fault or overload conditions, the ohmic loss of resistance R_L will increase and, owing to the heat caused by it, the temperature of ferrite core will rise. After the time t_Q, if the temperature of magnetic core arrives at the Curie temperature, the induced voltage of winding N_v disappears (thus turning on SCR and operating the no-voltage release to "off"), and breaks the overload current.

Figure 7 shows an inverse-time overcurrent relay devised by the author to protect against overheating the special transformer. Figure 8 shows the time-current characteristics measured when the circumference temperature ranged from 23°C to 26°C.

For this relay, the value of the Curie temperature is taken as the standard value and, therefore, the temperature rise of the protective device is limited to certain values, despite the temperatures around the protective device.

Therefore, if the operating temperature of the relay is connected with the limited temperature of the protective device, one need not adjust the definite time according to the circumference temperature conditions.

This relay is small in comparison with the induction disc relays or the induction cup relays, and operates accurately, without any chattering or bouncing, because there are no mechanical contacts in the process of detecting faults and amplifying the signal current.

As the voltage source for this relay, the same power supply as that of the load can be utilized so that it has another advantage in that a special power supply is not needed. In case of a fault in the voltage source, the no-voltage release operates, and when the fault of power source is corrected, no-voltage is applied in the relay or the load, unless the no-voltage release is closed; thus, this relay is free from danger

This relay spends few volt-amperes, so it can be utilized for the overload protection of the small devices.

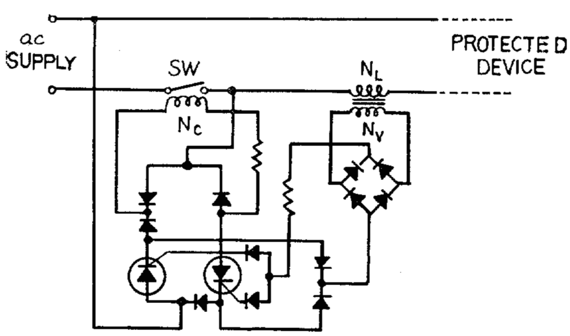

Fig. 6. Basic circuit of overcurrent relay.

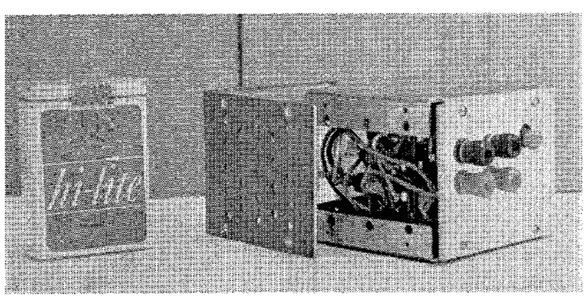

Fig. 7. View of overcurrent relay using ferrite core.

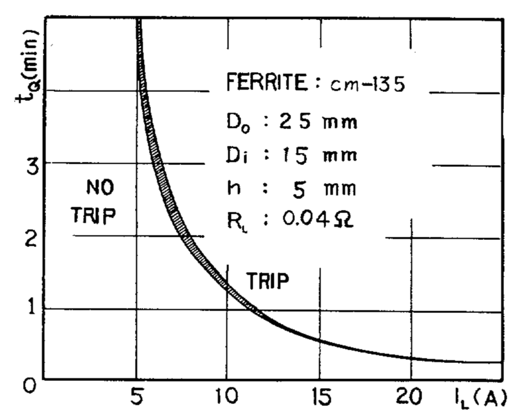

Fig. 8. Measured characteristics of inverse-time relay.

Application to Timing Unit for Long Delay

When long delay is needed, RC circuit, or the magnetic cores, have been used [1], [2], but in these cases there are some weak points in that the apparatus are apt to be large or the setting of delay time will deteriorate in precision. If the characteristic of the ferrite cores with low Curie temperature is utilized, a small-sized timing unit for long delay can be made. The practical use of this is examined.

As seen from (5), if the size of ferrite cores, resistance R_L, etc., are decided, t_Q is decided by the current I_o as input signal. Namely, if in the circuit of Fig. 2(a) the input signal current I_o is made to flow through the constant-current device into winding N_L and the induced voltage across winding N_v disappears after a certain time owing to the ohmic loss of resistance R_L, a delay circuit can be made by adding the required circuit. By this method, it is easy to get long delay by reducing the value of resistance R_L to a small amount.

However, as shown in (5), if the circumference temperature changes, t_Q, as the time in which the temperature of the magnetic core arrives at the Curie temperature, will vary, even if the input current I_o is constant. Figure 9 shows the relation between the circumference temperature and the delay time, in contrast to various values of input current I_o calculated by the use of (5).

From this figure, one will see that if the input current is large, t_Q is constant in the region of temperature at which, in general, the delay circuit is used. But when I_o is small, t_Q changes in considerable degree, according to the variation of the circumference temperature. In such cases, if the

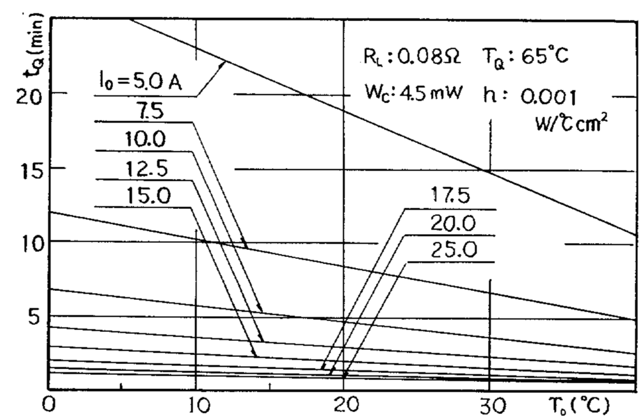

Fig. 9. Time vs. temperature curves with various values of current I_0.

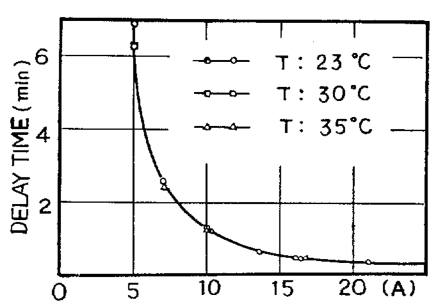

Fig. 10. Characteristics of delay circuit.

timing unit is put into an oil tank having a large heat capacity, or into the temperature control room, the timing unit can be used as an independent timing unit for delay, free from the influence of the circumference temperature.

If the input current against the circumference temperatures is compensated by the following relation, t_Q can be kept constant. The current I_x to flow at the circumference temperature T_x is expressed as follows:

$$I_x = I_0((T_Q - T_x)/\{(T_Q - T_0)[1 + \alpha(T_x - T_0)]\})^{1/2} \quad (6)$$

where α is the temperature coefficient of resistor, R_L. Figure 10 shows the characteristics really sought when compensation is made by the use of (6) for cases in which the circumference temperatures are 35°C, 30°C, and 23°C. It shows that t_Q is constant in spite of the variation of the circumference temperature.

As already mentioned, if the ferrite cores with low Curie temperature are utilized, a small-sized delay apparatus with long delay time can be easily made.

Application to Thermomagnetic Generator

For the generation of electric energy, the method of moving the conductor by crossing the magnetic field is generally used. On the contrary, however, it is possible to generate electric energy by fixing the conductor, and moving the magnetic field crossed with it, too.

The ferrite cores described in this paper have characteristics in that their Curie temperatures are low, and the flux vanishes suddenly near the Curie temperature; the magnetic characteristic has a comparatively rectangular hysteresis loop, and the residual flux is also large. Therefore, it is possible for the winding to generate electric power by having a winding on the ferrite core, and by changing the flux of the magnetic core through repeated heatings and coolings near the Curie temperature [3]–[5]. The author examined the utility of the transducer for conversion of heat energy to electric energy by this method. It was found from the results thus obtained, that this method has some advantages in that no permanent magnet is needed, operating temperatures are low, etc.

Wind the bias winding N_b, and the load winding N_L, as shown in Fig. 12, on the ring-formed ferrite core whose flux vs. temperature characteristic is shown in Fig. 11. If the residual flux is represented by Φ_m, the relation between the flux Φ and the temperature T of the ferrite core is expressed by the following equation:

$$T = T_Q - \Phi(T_Q - T_P)/\Phi_m. \quad (7)$$

If the quantity of the heat given to the ferrite core in unit time is represented by Q, the heat capacity by C_f, and the heat transfer coefficient by h, if the temperature of the magnetic core rises uniformly, then there can be found the following equation:

$$T = (T_m - T_0)[1 - e^{-Q/C_f(T_m - T_0)t}] + T_0 \quad (8)$$

where T_o is the circumference temperature, and T_m is the temperature of the ferrite core when $t = \infty$. Curve A in Fig. 13 shows the relation expressed by (8).

Substituting (7) into (8), we obtain the relation between the temperature and the value of flux expressed as a function of t.

$$\Phi = \frac{\Phi_m}{T_Q - T_P}\{T_Q - T_o - (T_m - T_o)[1 - e^{-Q/C_f(T_m - T_o)t}]\} \quad (9)$$

Curve C in Fig. 13 shows the relation expressed by (9). t_P and t_Q, as the time in which the temperature of ferrite core arrives at T_P and T_Q, respectively, can be obtained from (8).

As seen from Fig. 13, the voltage generates the winding N_L as long as $t_P \leq t \leq t_Q$.

$$e = -\frac{N_L \Phi_m Q}{(T_Q - T_P)C_f} e^{-Q/C_f(T_m - T_o)t}. \quad (10)$$

Equation (10) shows that, as the residual flux of the core becomes larger, T_Q draws nearer T_p in value, the quantity of supply heat Q is larger, and the generated voltage of the transducer will increase.

If the quantity of heat supplied to the ferrite core becomes zero, the temperature of the ferrite core falls according to

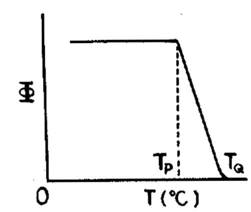

Fig. 11. Typical characteristic of flux vs. temperature.

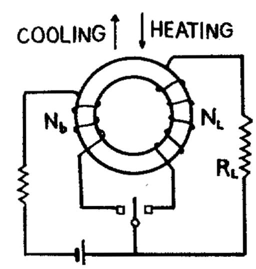

Fig. 12. Basic circuit of thermomagnetic generator.

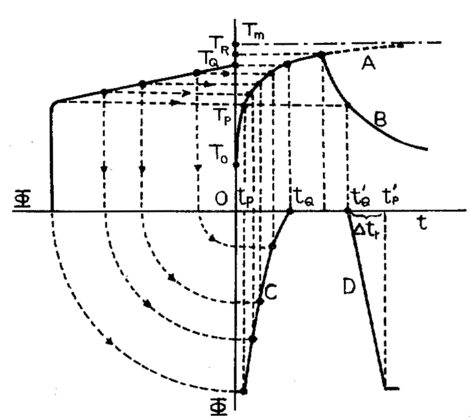

Fig. 13. Graphical analysis of flux vs. time curve of ferrite core.

the following equation:

$$T = T_o + (T_R - T_o)e^{-h/Cft}. \quad (11)$$

Curve B in Fig. 13 shows the relation expressed by (11).

After the magnetism of the ferrite core is recovered at $t = t_Q$, the bias voltage E_b is supplied, letting the flux arrive at the positive saturation. If the supplied time of the bias voltage to the ferrite core is represented by Δt_r, Δt_r is expressed by the following equation:

$$\Delta t_r \cong N_c \Phi_m / E_b. \quad (12)$$

After time Δt_r, the bias circuit is opened and the ferrite core holds the residual flux Φ_m. While the bias voltage is supplied, if the load winding N_L is opened, the voltage of bias winding must supply only about one quarter the hysteresis loss of the ferrite core. Curve D in Fig. 13 shows this relationship.

If three strokes, namely heating, cooling, and bias voltage, are repeated, the electric power can be generated on winding, N_L, in the stroke of heating. A simple elementary experiment has been carried out in regard to this method, and since the investigation is now being made, details will be reported at a later date.

Application to the Temperature Control System

As already mentioned, when heat input is given to the ferrite cores, if the permeability vs. temperature characteristic is used for the temperature reference, it is possible to carry out the temperature control by the use of the ferrite cores with low Curie temperature.

Figure 14 shows the circuit of the temperature control proposed. To avoid any time lag which would be found between the temperature in the tank and that of the ferrite core used as reference, the ferrite core was made to be a ring-formed one, 5 mm in the inside diameter, 10 mm in the outside diameter, and 3 mm in the height. For making the circuit, two cores were used, and a high-frequency magnetic amplifier with third winding was also used. Ferrite core 1 is for the purpose of measuring reference, and ferrite core 2 is an auxiliary core. Accordingly, the Curie temperature of ferrite core 2 is much higher than that of core 1. Terminal 1 1′ is the power source of 20 kc which was made with Royer's circuit [6] and terminal 2 2′, that for the heater of commercial frequency. N_h is an auxiliary winding, eliminating the hysteresis of the heater circuit switch.

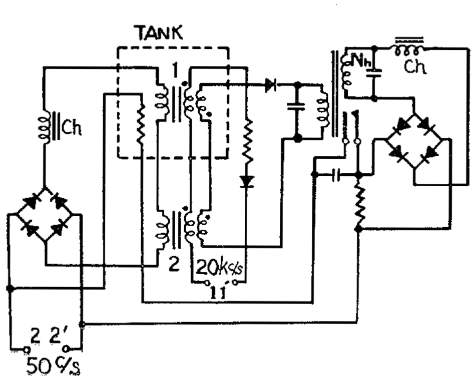

Fig. 14. Circuit of temperature control using ferrite cores.

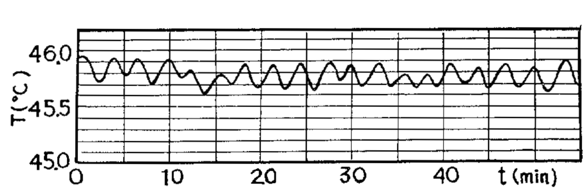

Fig. 15. An example of temperature control.

When the temperature in the tank rises above the Curie temperature, the flux of ferrite core 1 vanishes. On the other hand, the output voltage induced by core 2 is supplied to the output winding, N_L, and makes switch SW "open."

If the temperature in the tank falls below the Curie temperature, the magnetism of ferrite core 1 recovers, and the output voltages of magnetic cores 1 and 2 are added to the opposite direction. Since no voltage is supplied on the load winding N_L, switch SW is closed, and the tank is heated by the heater.

Figure 15 shows an example of temperature control. It is found that the control is carried out in the range of $\pm 0.2°$ C; SCR can be used instead of switch SW. To set up the temperature of the tank, ferrite core 1 must be exchanged. This device is simple in construction and claims an advantage in getting an exact temperature control.

Conclusion

The utility of ferrite cores which have the Curie temperature in the vicinity of the room temperature and suddenly change the permeability vs. temperature characteristic near the Curie temperature, have been described. An overcurrent relay, a temperature control device, and a timing unit for long delay were made by the author, using ferrite cores of this kind, and are practical devices. Furthermore, its application to a thermomagnetic generator, by improving the characteristics of the ferrite cores, is also considered useful.

In conclusion, the author finds that ferrite cores with low Curie temperature are among the important materials helping the development of a new field in electric devices.

Acknowledgment

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