Chapter 5 Technology roadmap

Section 1 Passive device design and its challenges

1.1 Material development based on an integrated discussion of the relationship between magnetic materials and circuit design parameters

Keywords: magnetic material parameters, circuit design parameters, model-based optimization

In power electronics, circuit designers/researchers and developers/researchers of magnetic components and magnetic materials have been discussing the design and performance of the same magnetic component based on different parameters, and they have not necessarily had an integrated discussion considering the relationship between these parameters. This is not favorable for discussing guidelines for future material development.

There are many parameters that indicate the characteristics of magnetic materials, but "permeability μ_r", "saturation flux density B_s" and " core loss per unit volume P_cv " are representative parameters that directly affect circuit design and performance as magnetic components. In addition to these, coercive force H_c and resistivity ρ are also important parameters, but we consider that P_cv is included here. On the other hand, in circuit design, "inductance L ", "maximum current I_p " and "core loss P_c " are the main parameters for inductors. In transformers, the main parameters are "capacitance S," "excitation inductance L_m " and "core loss P_c ". The parameters that connect magnetic material parameters and circuit design parameters are "core shape," "number of turns," and "gap length" for inductors, and "core shape," "number of turns," and "frequency" for transformers. The circuit designer or magnetic component designer determines these parameters to determine the relationship between the parameters of the magnetic material and the parameters of the circuit design. However, there are many degrees of freedom in determining these parameters, and they are often based on the designer's experience, etc., and are not uniquely determined, so the prospect is not good.

1.1.1 Conversion from circuit design parameters to magnetic material parameters using a simple magnetic component model

In this section, we use the example of a transformer to show that by connecting magnetic material parameters and circuit design parameters, we can incorporate the requirements from the circuit system side into the requirements for magnetic material performance and discuss the direction of future magnetic material development. Since the purpose of this section is to show the relationship between magnetic material parameters and circuit design parameters in a broad and clear manner, the magnetic components are specified in a model that is as simple and objectively determinable as possible, without regard to whether they can actually be manufactured (i.e., whether the shape of the magnetic core is commercially available or not is irrelevant, etc.). The specific procedure is shown in Fig. 5. The procedure is as shown in **Fig. 5.1.1.** 1, where various frequencies f and maximum magnetic flux B_m densities to be used are set for magnetic components (in this example, a transformer) that satisfy the given circuit side specifications using a brute force formula, the magnetic component design and performance evaluation as a magnetic component are performed using a simple model, and a certain optimal design The design that achieves the optimum performance is selected as the magnetic component design. The design that achieves the optimum performance is converted into magnetic material parameters, and the difference between the existing performance and the actually required performance is compared.

In order to design and evaluate the performance of magnetic components in a brute-force fashion, a model that can calculate the volume and loss of the component with only simple calculations is necessary. Here, we assume an EI core whose dimensions can be freely designed without regard to commercially available shapes, and express its window area and magnetic core cross-sectional area in terms of the given circuit specifications and f and B_m. The cross-sectional area A_c of the magnetic core can be calculated using the RMS value of the voltage V_rms1 applied to the primary winding and the number of turns N_1.

$$A_\mathrm{c} = \frac{\sqrt{2}V_\mathrm{rms1}}{2\pi f N_1 B_\mathrm{m}} \quad (5.1.1.1)$$

Figure 5.1.1.1 Flowchart of conversion from circuit design parameters to magnetic material parameters

The winding cross-sectional area is expressed as The cross-sectional area A_{w} of the winding can be calculated using the RMS value I_{rms1} of the rated current of the primary winding and the number of turns N_1.

$$A_{\mathrm{w}} = \frac{N_1 I_{\mathrm{rms1}}}{J_{\mathrm{m}} K_{\mathrm{u}}} \tag{5.1.1.2}$$

J_{m} is the assumed current density, and K_{u} is the assumed current density, and is the assumed occupancy ratio of the conductor cross-sectional area of the primary winding to the window area. The design is arbitrary, because both of the above A_{c} and the above A_{w} are included N_1 in the design. For example, there are designs in which the value of N_1 is made larger and the value of A_{c} is made smaller, and designs in which the value of N_1 is made smaller and the value of A_{w} is made smaller. In the design of commercial frequency transformers and rotating machines, there are methods to distribute these "loads" based on statistical information obtained from previous design examples. To simplify the analysis for the purpose of this study, the shapes of both the window and the magnetic core cross-section are assumed to be square, and the number of turns N_1 is determined such that $A_{\mathrm{c}} = A_{\mathrm{w}}$ .If the shape of the magnetic core has been determined, the core volume V_{c} and magnetic path length l can be obtained, and if the winding has a L-shaped shape with the cross section of the window area, the box volume (the smallest rectangular volume that can contain the shape of the magnetic core and winding) can be obtained.

Similarly, a model that can be simply calculated is needed for the magnetic core loss. Here, the core loss per unit volume P_{cv} is determined from f and B_{m} using the Steinmetz method. The magnetic core loss P_{c} is obtained by multiplying this by V_{c}. For simplicity, no gap is assumed, and the inductance of the winding can be obtained from l and the magnetic permeability μ_r of the material. This is the excitation inductance L_{m} .

P_{c} and Box Volume represent the performance of a magnetic component, the design that optimizes these two variables is not uniquely determined. Here, as a simplified method, we give the frequency f and evaluate the design that minimizes the box volume. In other words, the basic approach is to maximize B_{m} relative to B_{s} while establishing a certain margin. However, since the heat generation density of the magnetic core P_{cv} is a heat generation density, there is a restriction that it must be less than a certain value, and it is necessary to select a feasible design that satisfies this restriction, so in some cases, a smaller value B_{m} is selected. In some cases, a smaller value L_{m} is selected because it is necessary to select a feasible design that satisfies this constraint.

Extract $P_{\mathrm{cv}}, B_{\mathrm{m}}, L_{\mathrm{m}}$ at the optimal design point corresponding to the frequency f determined above. L_{m} is related to the excitation current, it can also be indicated by the required μ_r, by imposing appropriate conditions, such as keeping the excitation current below a certain ratio to the load current. By comparing these parameters with those currently possessed by the assumed magnetic material $P_{\mathrm{cv}}, B_{\mathrm{s}}, \mu_r$, it is possible to discuss which of these parameters are excessive in this application/transducer specification, and which parameters are bottlenecks.

1.1.2 Case Study in High Frequency Transformers with Ferrite

As an example, a design example of a high-frequency transformer using Mn-Zn ferrite (TDK N87) is shown below. **Table 5.1.1. 1**shows the specifications of the high-frequency transformer under consideration, **Table 5.1.1.2 shows the** assumed winding design conditions, and **Table 5.1.1.3** shows the assumed material properties of the ferrite. The occupancy factor and current density are greatly affected by the required insulation capacity, operating frequency, and whether or not Litz wire is used, but they are assumed here to be uniformly constant. In the calculation of magnetic core loss, the magnetic flux density is assumed to vary sinusoidally in time and is calculated by the Steinmetz method. The maximum magnetic flux density used is 0.3 T, and 300 kW/m^2 (300 mW/cc) is given as the magnetic core loss per unit volume as a constraint condition.

Table 5.1.1.1 Specifications of high-frequency transformers to be considered

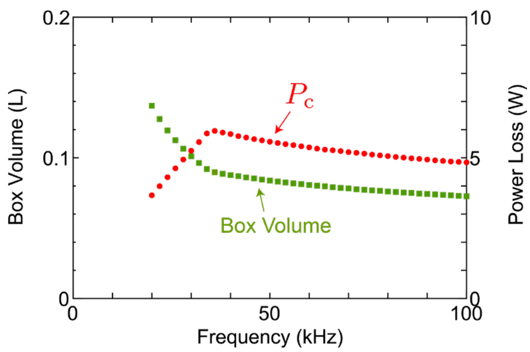
Power capacity	4.75 kVA
Primary voltage	1767 V
primary current	2.687 A
Secondary voltage	not stipulated
secondary current	not stipulated

Table 5.1.1.2 Assumed winding design conditions

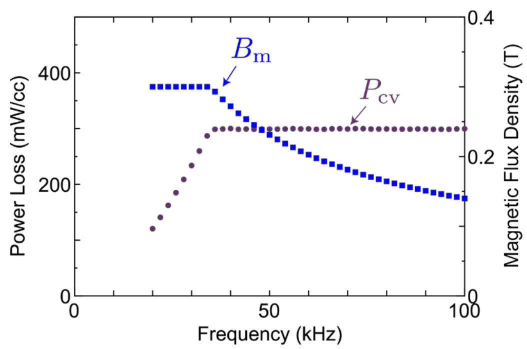
Current density J_m	3 A/mm^2
Primary winding occupancy K_u	0.1

Table 5.1.1.3 Assumed magnetic core material properties

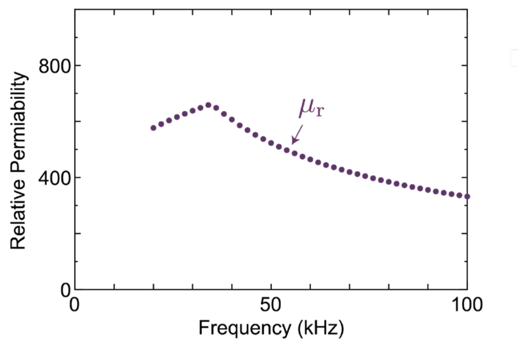
Saturation flux densityB_s	0.41 T
initial permeability	2200
Steinmetz coefficient k	1.69E-01 W/m3
Steinmetz coefficient α	1.6349
Steinmetz coefficient β	2.2527



(a) Core Losses and Box Volume P_c



(b) Maximum flux density B_m and core loss per unit volume P_{cv}



(c) Permeability required to achieve 5% excitation current μ_r

Figure 5.1.1.2 Example of conversion results from circuit design parameters to magnetic material parameters

Figure 5.1.1.2 shows the results of a simplified optimal design under these conditions and the parameters of the magnetic material to realize the design. **Figure 5.1.1.2** (a) shows the core loss P_c and box volume as the performance of magnetic components. Basically, the higher the frequency, the smaller the box volume. As shown in **Figure 5.1.1.2** (b), the box volume reaches the upper design limit of 0.3 T at low frequencies B_m, but at frequencies above 35 kHz, a value B_m smaller than 0.3 T was selected due to the constraint condition P_{cv} of

Figure 5.1.1.3: Degree of utilization of magnetic material parameters and image of material properties required by the circuit design side

this means that above 35 kHz, the core loss P_c decreases with increasing frequency due to the decrease in volume. In other words, only when copper loss is not considered at all, both volume and loss decrease further above 100 kHz in this case, which means that the optimal design as a magnetic component is above 100 kHz. In reality, however, the loss is expected to increase significantly due to the proximity effect of the windings and the skin effect as the frequency increases.

The excitation inductance L_m was very large, more than 0.1 H in this case. This was converted to reactance at each frequency, and the excitation current flowing when the voltage was applied to the primary winding was calculated to be about 1% of the assumed primary current, a very small value since 5% is generally acceptable. This indicates that the magnetic permeability of this material is sufficiently high. Conversely, we determine the value of L_m such that the magnetizing current is 5% of the load current, and from that, we calculate the required μ_r; this is shown in Figure 5.1.1.2(c). According to this result, even if the initial permeability of the material used in this case is lower than 2200 and 1/3 of that μ_r, the prescribed functionality can be achieved. This is especially true when the frequency is high.

1.1.3 Discussion of required material properties using the results of conversion to magnetic material parameters

The results of this case study can be considered as follows. As the chart on the left side of **Figure 5.1.1.3** shows, in this case, above 35 kHz, the performance of the magnetic component is dominated by P_{cv} and P_{cv} is maximized by the performance of the assumed material. On the other hand, for B_s and μ_r, only a part of the performance of the assumed material is used. In most cases, not only in this case, one of the parameters is considered to be the overall governing parameter, while the other parameters are not fully utilized.

Given this, the performance of the optimal design would be better if the material were as shown in the chart on the right side of **Figure 5.1.1.3**. In this case, a smaller P_{cv} preferred, and as a trade-off , B_s and μ_r may be somethat lower. Since large changes in magnetic material parameters will change the optimal design, it is not guaranteed that the same trend will occur with improved magnetic materials, but it is possible to indicate the direction of performance improvement from the materials assumed at this point in time.

In reality, however, it is necessary to consider many cases for each application and capacity, and to improve the model for more accurate evaluation of loss and volume. In particular, although not included in this case study, the increase in AC resistance due to high frequency has a significant impact on some applications, and it is necessary to evaluate and optimize the loss and volume using a model that takes this into account. However, modeling techniques for magnetic components have advanced for model-based design optimization, which has been studied in recent years, and it can be said that more accurate evaluation is now possible. Using these modeling techniques developed for model-based optimization, it will be necessary in the future not only to obtain optimal designs from existing material properties, but also to use them in the reverse direction to discuss even the direction of development of material properties as described in this section. [Takanori Isobe]

1.2 Technological Trends in Magnetic Elements (excluding iron-nitrogen)

Keyword: Fe-based amorphous alloy materials, nanocrystalline alloy materials, high saturation magnetic flux density

1.2.1 Introduction.

For further development of power devices, compact and high-performance magnetic elements that can operate under various conditions are required. Soft magnetic materials with high saturation magnetic flux density (B_s) and low loss are essential to realize such devices [(1)-(6)]. These materials must be able to maintain stable fundamental properties over a wide temperature and frequency range. They must also have sufficient mechanical strength and excellent workability (e.g., cutting, winding, annealing), i.e., ease of processing suitable for industrial production. Environmental resistance (e.g., corrosion stability) is also an essential property to ensure long-term reliability.

Traditionally, Fe-Ni, Fe-Si-Al, ferrite, and Co-based amorphous alloys have been used as materials satisfying these requirements. Recently, Fe-based amorphous alloy materials and nanocrystalline alloy materials have attracted attention as promising alternatives to conventional materials because of their high B_s and low loss. Amorphous alloy materials are produced by the rapid solidification method and consist mainly of transition metals (Fe, Co, Ni, etc.) and metalloids (Si, B, etc.), with small amounts of difficult-to-melt metals such as Nb, Mo, Zr, and Hf sometimes added to stabilize the amorphous structure. Nanocrystalline alloy materials, on the other hand, are formed by controlled crystallization of amorphous precursors and have a unique microstructure in which fine nanocrystals are dispersed within the residual amorphous matrix. For these materials, we are currently working on research issues such as workability of amorphous alloys, control of the crystallization process of nanocrystalline materials, and development of materials with compositions that have less environmental impact, aiming to further improve their performance and expand their range of applications.

As mentioned above, Fe-based amorphous alloy materials and nanocrystalline alloy materials have higher B_s than conventional soft magnetic materials, and magnetic cores made of these materials can be used without magnetic saturation in stronger magnetic fields. They also have lower loss than conventional soft magnetic materials and excellent high-frequency magnetic properties. These features are expected to lead to the realization of compact magnetic elements with high power density.

1.2.2 Academic Scientific and Technical Issues

Although Fe-based amorphous alloy materials and nanocrystalline alloy materials have excellent soft magnetic properties, they pose inherent scientific and technical challenges. There are two main scientific issues in the case of Fe-based amorphous alloy materials. The first is how to maintain the amorphous state, since heating causes crystallization and significant degradation of magnetic properties. The second is how to achieve both low magnetostriction and high saturation magnetic flux density, since reducing magnetostriction by substituting magnetic elements leads to a decrease in the saturation magnetic flux density of the material itself. On the other hand, in the case of nanocrystalline alloy materials, since multi-system alloys containing Cu, Nb, Zr, etc. are usually used, it is essential to ensure grain size stability under repeated thermal and magnetic loading, and if grain growth progresses, soft magnetic properties are impaired. Therefore, the alloy design promotes uniform crystal nucleation and suppresses grain growth.

As a technical problem, Fe-based amorphous alloy materials have a relatively high Vickers hardness of about 900 Hv, but they are brittle and poor in workability, so tools with high hardness and precise control of processing conditions are required when punching is performed. In addition, wear of the die is also noticeable, resulting in a short tool life. Therefore, it is necessary to develop devices that can be processed without using the punching method, to improve the materials themselves, and to develop measures to improve the efficiency of processing during punching, in order to use them more extensively. In addition, residual stress is generated in the cast state, and in many cases, heat treatment is applied to improve soft magnetic properties and control the shape of the *B*-*H* curve. Temperature control is important in this process, because if the temperature is lower than the optimum temperature, stress relaxation is insufficient, and if the temperature is higher than the optimum temperature, the desired magnetic properties may not be obtained due to excessive embrittlement and, in some cases, crystallization.

On the other hand, nanocrystalline alloy materials obtained by heat treatment of the amorphous phase have the same problems as the thin strip-shaped amorphous alloy materials described above, and the progression of embrittlement due to heat treatment makes processing more difficult. Basically, it is currently difficult to process nanocrystalline alloys using a die after nanocrystallization, and it is necessary to develop processes such as the development of processing methods other than dies, such as lasers, or punching before heat treatment. In nanocrystalline alloy materials, nanocrystals are obtained through precipitation of the crystalline phase by heat treatment of the material obtained in an amorphous state. In this process, the volume fraction of the nanocrystalline phase and the residual amorphous phase depends on the heat treatment conditions represented by the heat treatment temperature and heat treatment time, so strict temperature control is required to obtain the desired magnetic properties (e.g., magnetostriction and magnetic permeability). During this heat treatment, an exothermic reaction occurs when crystal grains precipitate from the amorphous phase, and temperature control must take this situation into account. Since volume shrinkage occurs during the transformation from the amorphous phase to the nanocrystalline phase, it is also necessary to consider this point for some devices. In addition, nanocrystalline alloy materials require precise heat treatment to maintain grain size. All of these factors are dependent on expensive or rare alloying elements, and thus remain a challenge from the viewpoint of mass production and sustainability.

Furthermore, the environmental impact and resource constraints of key elements such as Cu, Nb, and Zr have become an issue, and the development of recycling technologies is underway. For future applications in high-frequency and small electronic devices, compatibility with advanced processing technologies such as thin-film formation, three-dimensional structuring, and micro-patterning will be essential. Therefore, it is essential to develop new processes consistent with microfabrication technologies in addition to the conventional thin strip-based fabrication methods.

For material development, the cost of raw materials should also be considered. In the selection of magnetic elements, it is necessary to consider the balance between performance requirements and cost. The cost of magnetic elements also affects the cost of the entire power electronics circuit system. Therefore, optimization of cost performance is one of the most important factors.]

[Mai Phuong Nguyen , Motoki Ohta, Satoshi Okamoto, Yasushi Endo]

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1.3 Capacitor Technology Trends

Keyword: Conductive polymer solid capacitor, PEDOT:PSS, High withstand voltage, High heat resistance

1.3.1 Ceramic Capacitors

In general, ceramic capacitors are characterized by their excellent heat resistance, relatively high dielectric constant, small size and high capacitance by layering, and excellent frequency characteristics due to their low ESR. Therefore, they are mainly used in smoothing capacitor and snubber capacitor applications, as well as in high-frequency resonance capacitors by taking advantage of their excellent frequency characteristics.

In particular, multilayer ceramic capacitors are required to be further miniaturized and increased in capacitance due to the thinner and higher performance of information terminals such as smartphones and the increase in the number of users of electronic devices, automobiles, and other high-performance devices, and the development of components including dielectrics and process technology is being promoted to achieve this. In order to realize this trend, the development of components including dielectrics and process technology is being promoted. Different technological trends include high-frequency compatibility with the increasing frequency of LSIs and compatibility with high voltage, high current, and high power capacity for power electronics applications. In power electronics applications, the DC bias characteristics of ferroelectric $BaTiO_3$-based materials (a characteristic in which the dielectric constant decreases with the application of voltage) has been an issue, but improvements are being made by improving the composition of the dielectric materials. As a different strategy, multilayer ceramic capacitors using antiferroelectric materials instead of ferroelectric materials have been proposed and put into practical use. These capacitors utilize the positive bias characteristics of antiferroelectric materials (the dielectric constant increases with the application of voltage) and have the characteristic of large effective capacitance even under DC bias voltage. Since large effective capacitance is required for all applications, development of materials and process technologies is expected to be promoted to realize thinner dielectric layers and higher reliability in the future. Currently, lead specifications for dielectric ceramic in capacitors with a rated voltage of less than 125 V AC or 250 V DC are regulated by the RoHS Directive (1). Prevention of short-circuit failures due to dielectric breakdown of ceramic capacitors under high voltage is an extremely important issue because it greatly affects the reliability of power electronics equipment. However, dielectric breakdown of ceramics is a complex phenomenon involving not only the intrinsic properties of the material itself but also various factors such as defects and grain boundaries. Therefore, it is difficult to solve this problem only by developing new materials. One possible policy is to increase the intrinsic dielectric breakdown strength of the material as much as possible by widening the energy band gap through the selection of the constituent elements, and to use a sufficiently lower rated voltage, but in this case, the dielectric constant is sacrificed due to the inverse proportional relationship between the energy band gap and the dielectric constant. Therefore, to solve the problem of short-circuit breakdown in ceramic capacitors, it is necessary to create new methods to avoid dielectric breakdown in advance, such as designing special electrode patterns that intentionally cause sequential degradation of capacitors under high voltage, or developing new technologies to detect the precursors of dielectric breakdown. The development of new methods to avoid dielectric breakdown in advance and multifaceted efforts in combination with the creation of new methods are considered necessary.

[Hiroki Taniguchi, Manabu Hagiwara, Sakyo Hirose]

1.3.2 film capacitor

Film capacitors using polypropylene (PP) film as dielectric film have excellent electrical characteristics (low loss, temperature characteristic stability, etc.) and high reliability, but the usable upper temperature limit is not so high. Currently, PP film capacitors are often used at an upper capacitor internal temperature of 85 ℃ (for industrial applications) or 105 ℃ (for automotive applications).

In recent years, as equipment has become smaller and denser, film capacitors have also become smaller and more energy dense, and the use of next-generation semiconductors such as SiC has led to higher temperatures in the operating environment, increasing the need for film capacitors with higher heat resistance, lower loss, and higher heat dissipation. Until now, the need for high heat resistance has been met by improving the heat resistance and withstand voltage of PP film, suppressing heat generation by designing film capacitors, and reviewing heat dissipation.

PP film is made of a crystalline organic polymer material. Crystalline polymers are composed of crystalline and non-crystalline portions. As the temperature rises, the molecular motion of the non-crystalline portion first becomes active, and as the temperature further rises, the molecular motion of the crystalline portion also becomes active, and finally the crystalline portion breaks down and becomes fluid (melting point: 160-170 ℃).

When used as a PP film capacitor, it must be used in a temperature range where the crystalline state is stable. The upper temperature limit for use as a capacitor has been raised as PP film has been improved. The service temperature varies depending on how the film capacitor is used (operating voltage, load current, expected life, etc.), but for short periods of time, it is becoming possible to handle temperatures up to about 115 ℃.

The future challenge for film capacitors will be to achieve even higher heat resistance and higher voltage resistance. The melting point of PP film, which is currently the most commonly used dielectric film, is 160-170 ℃. If PP film is used as a dielectric film, further improvement in heat resistance is approaching its limit, and in the high temperature range of 125 ℃ or higher, a high heat-resistant film other than PP film is required.

However, compared to PP film, which features low loss, high withstanding voltage, and good self-healing function, PP film is inferior in any of these characteristics, so it is expected to develop dielectric films that match the way film capacitors are used, such as high heat resistance and high withstanding voltage. Therefore, it is expected to develop dielectric films that match the way film capacitors are used, such as high heat resistance and high voltage resistance. Since the operating voltage range of film capacitors used in power electronics applications (several hundred to several thousand V) is wide, it may be necessary in the future to select dielectric films based on the characteristics of high heat-resistant films, depending on the application. Materials other than film capacitors (e.g., exterior materials) will also need to be compatible with high heat resistance and high withstand voltages.

[Ryuhei Koyama.]

1.3.3 electrolytic capacitor

Electrolytic capacitors are important passive components used in a variety of fields, including power electronics equipment. However, there are some fundamental issues in their performance. In particular, the limitations of withstand voltage and thermal resistance are important technical issues that must be overcome in next-generation applications that require high-voltage operation and operation in high-temperature environments. For this reason, research and development aimed at increasing the voltage and heat resistance of electrolytic capacitors is being actively pursued both in Japan and overseas, and has become an extremely important topic in determining future technological trends. The following is an overview of the trends and prospects.

(1) Expectations for Conductive Polymers with Higher Withstand Voltage

Among various types of capacitors, aluminum electrolytic capacitors are characterized by their high capacitance. Aluminum electrolytic capacitors can be roughly classified into three types according to the electrolyte used: (1) electrolyte type, (2) conductive polymer type, and (3) hybrid type of electrolyte and conductive polymer. The electrolyte type is advantageous for high withstand voltages because it can self-repair defects in the dielectric alumina during operation, and capacitors with withstand voltages exceeding 500 V are commercially available. On the other hand, the high resistance of the electrolyte used results in a large equivalent series resistance (ESR) and low ripple current tolerance [(2)].

Solid conductive polymer capacitors, which use a conductive polymer with high electrical conductivity in place of electrolyte, were developed in the 1990s as a new capacitor with excellent high-frequency characteristics that can reduce ESR because the electrical conductivity of the conductive polymer is significantly higher than that of the electrolyte [3][4]. This capacitor is a representative practical example of the conductive polymer discovered in the 1970s, and its market has grown to over 300 billion yen. Solid conductive polymer capacitors do not have the risk of liquid leakage that causes electrolyte-type failures, and the excellent heat resistance of conductive polymers has led to high expectations for these capacitors as high heat-resistant capacitors. However, the withstand voltage of conductive polymer solid capacitors is low, and the rated voltage of mass-produced capacitors is limited to 50 V.

Around 2010, a hybrid type capacitor was developed to improve withstand voltage while maintaining the excellent high-frequency characteristics of conductive polymer solid capacitors. These capacitors use a combination of electrolyte and conductive polymer as the electrolyte, and have the same electrical conductivity as conductive polymers, but the presence of the electrolyte makes it possible to improve the withstand voltage. However, the rated voltage of mass-produced products, even of the hybrid type, is about 100 V, which is a large gap from the withstand voltage of over 400 V required for smoothing capacitors used in inverters and other power electronics equipment. Solid conductive polymer capacitors are advantageous in that they do not use any liquid, and therefore, they are expected to have high durability without failures caused by liquid leakage, and they also have improved heat resistance because they do not use electrolyte. In INNOPEL, development of conductive polymer solid capacitors with withstand voltage of 450 V or higher is underway. Furthermore, in the mobility field such as electric vehicles (EV) and in the power conversion field using renewable energy such as photovoltaic and wind power generation, there will be a need for capacitors with a withstand voltage of over 1 kV. The self-healing property of dielectric has been one of the issues for conductive polymer solid capacitors, and it has been reported that this property is also manifested in these capacitors [5]. This suggests further possibilities for conductive polymer solid capacitors in the field of power electronics. This paper describes the prospects of this type of capacitor from the following perspectives.

(2) Potential of conductive polymer solid capacitors with voltage resistance equivalent to electrolyte type electrolytic capacitors

In the development of conductive polymer solid capacitors under the "Basic Technology Research and Development Project for Innovative Power Electronics" of the Ministry of Education, Culture, Sports, Science and Technology of Japan, the introduction of a new conductive polymer with controlled electrical conductivity and a high-resistance layer on the dielectric surface have revealed the possibility of conductive polymer solid capacitors with a withstand voltage of 450 V. The electrical conductivity of conducting polymers of the poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) system is correlated with their crystallinity, and the introduction of alkyl groups into PEDOT:PSS and the type of alkyl groups, the The crystallinity and electrical conductivity can be controlled by the introduction of alkyl groups into PEDOT:PSS, the type of alkyl groups, and the ratio of PEDOT to PSS. In addition, polyhydric alcohol additives added to PEDOT:PSS also have a significant effect on the withstand voltage [6]. The optimization of conductive polymers is expected to further expand the possibilities of conductive polymer solid capacitors with a voltage holding capability of over 500 V.

On the other hand, it has become clear that the interface design between the dielectric and the conductive polymer is also important for improving the withstand voltage. The dielectric of an aluminum electrolytic capacitor is formed by anodic oxidation of the aluminum substrate in an electrolytic solution such as a boric acid solution, and dielectric breakdown occurs during the formation as the formation voltage increases. It has long been known that the breakdown voltage (E_B) during anodic oxidation increases linearly with the logarithm of the electrolyte resistance (ρ_e) as in the following equation (5.1.3. 1)[7].

$$E_B = A + B \log \rho_e \qquad (5.1.3.\ 1)$$

Based on this knowledge, the breakdown voltage during anodic oxidation of aluminum was also reported in 2018 with the result that the breakdown voltage is more than 1500 V even by introducing a high-resistance layer (hydrated porous alumina layer) on the anodic oxidation surface [8]. This behavior regarding dielectric breakdown during anode oxidation is also useful for improving the breakdown voltage during the drive of conductive polymer solid capacitors. Recently, Quintero et al. demonstrated that when a nanovoid dispersion layer is formed on the dielectric surface by rehydrating the crystalline alumina dielectric film produced by anodic oxidation in a boric acid solution after hydration treatment and then applying a PEDOT:PSS conductive polymer, a high-resistance layer is formed in which a small amount of PEDOT:PSS PEDOT:PSS conductive polymer is then applied to the nanovoid dispersion layer, a high-resistance layer is formed with a small amount of PEDOT:PSS permeating the nanovoid dispersion layer. The introduction of this high-resistance layer into the dielectric/conductive polymer interface has led to the realization of breakdown voltages that exceed the anodic oxidation voltage, and the importance of this interface design has been discovered.

Based on the above approaches from conductive polymers and interface design, there is a growing technical possibility that the withstand voltage of conductive polymer solid capacitors can reach much higher voltages than the current mass-produced capacitors (≤ 50 V). On the other hand, new challenges may arise in the realization of 1 kV class conductive polymer solid capacitors. One of them is the control of the etch pit size of the electrode foil. For example, for a capacitor with a withstand voltage of 1 kV, the anode oxidation voltage for dielectric formation must be 1.2 kV or higher. At this time, the thickness of the dielectric alumina layer formed in the pit exceeds 1 μm , and as a result, it may not be possible to secure pores that can be filled with conductive polymers in the pit. Although it is possible to increase the pit size to some extent by dissolving, etc., in this case, fusion with adjacent pits may occur, and even if an etched foil is used, a sufficient increase in the spreading ratio will not occur, which means that the required electrical capacitance may not be obtained.

Two approaches can be considered as countermeasures against this problem. One is to change the dielectric to a material other than alumina and to reduce the thickness of the dielectric film that can withstand a voltage of 1 kV. The candidate is silica. While crystalline alumina requires a film thickness of about 1 nm to sustain a voltage of 1 V, silica has a thickness of 0.39 nm, less than half that of alumina [9]. In fact, it has been reported that the dielectric film thickness of an anodically oxidized sample of aluminum coated with SiO_2 by the Sol-Gel method is thinner than that of alumina alone, and the electrical capacitance is also increased [10][11]. If a high dielectric withstand voltage can be maintained with a thin dielectric, it will be possible to fabricate 1 kV class capacitors by utilizing the current etched foils in the future. Another approach is the development of new electrode foils that can replace aluminum etching. Recently, development of three-dimensional lamination technology using metal powder has been progressing. In Japan, Toyo Aluminium K.K. has developed a powder-laminated foil [12], and its application to capacitors is expected to expand in the future. In China, the development of capacitors using powder-laminated foil is also progressing [13][14]. Further development of this technology is expected to lead to the development of electrode foils with a porous structure suitable for high-voltage capacitors, and this lamination technology also has the advantage of reducing the environmental burden in comparison with etching technology involving the dissolution of aluminum.

(3) The Challenge of Heat-Resistant Capacitors

In air, PEDOT:PSS thermally degrades at temperatures below 100 °C and its electrical conductivity decreases [15], but in inert gas, good thermal stability has been reported [16]. Therefore, as long as PEDOT:PSS is used in an environment where the atmosphere can be shut off, it shows excellent heat resistance, and conductive polymer solid capacitors are also expected to exhibit high heat resistance. On the other hand, in terms of withstand voltage, it is desirable to lower the crystallinity of PEDOT:PSS to lower its electrical conductivity, which means that the thermal stability of PEDOT:PSS is lowered. Therefore, the adjustment of conductive polymers in the direction of increasing withstand voltage and increasing heat resistance are opposite to each other, and PEDOT:PSS should be optimized according to the desired withstand voltage and heat resistance.

The heat resistance of capacitors currently envisioned is 150 to 200 °C, but if higher heat resistance at higher temperatures is required in the future, it will be necessary to develop conductive materials that are substitutes for conductive polymers. A low-cost, heat-resistant inorganic aqueous nanoparticle ink that can be filled into the pits of electrode foils is expected to be one candidate, and breakthroughs in research on such materials are awaited.

[Hiroki Habasaki]

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Section 2　Future Challenges

2.1　Understanding Magnetostriction

Keyword: Magnetostriction, Magnetostriction measurement method, Anomalous loss increase, Excitation noise

When a magnetic field is applied to a magnetic material to magnetize it, a slight change in the outer shape is called magnetostriction (magnetic strain). The change in outer diameter due to magnetostriction is approximately 1/10,000 to 1/10,000,000 of the dimensions of the material itself. The magnetostriction of soft magnetic materials varies greatly with material composition. This material-dependent change in magnetostriction has a significant effect on the characteristics of passive components. This section outlines the magnetostriction of typical soft magnetic materials, the problem of magnetostriction in passive components, methods for measuring magnetostriction, noise in magnetic components, causes of sound, effects of structure and materials, relationship with circuit operation, and design methods for noise reduction.

2.1.1 Magnetostriction of materials and the problem of magnetostriction in passive components

The saturation magnetostriction of typical soft magnetic materials is shown in **Table 5.2.1.1** [1,2]. Pure iron is -7 ppm, Ni-Fe alloys (78 Permalloy), Fe-Si-Al alloys (Sendust) and Co-based amorphous alloy materials are almost zero, Fe-based amorphous alloy materials and nanocrystalline materials are about 15-30 ppm, spinel ferrite materials (Mn-Zn and Ni-Zn) are almost zero. All of these saturation magnetostrictions are physical properties of materials in bulk or thin strip form. On the other hand, in the case of magnetic core materials, the magnetostriction of the fine particles themselves is treated as being equivalent to that of bulk or thin strip materials, but the actual magnetostriction of the fine particles alone has not been measured, so it is unknown. In addition, when passive components are formed with resins or windings, internal stress is applied to the soft magnetic material, which is expected to cause a significant change from the magnetostriction of the material itself.

Table 5.2.1.1 Saturation magnetostriction of typical soft magnetic materials [1,2]

材料	飽和磁歪 λ_s (×10^{-6})
純鉄	－7
Ni-Fe 合金 （78 パーマロイ）	~0
Fe-Si-Al 合金 （センダスト）	~0
Fe 系アモルファス合金	20－30
Co 系アモルファス合金	~0
Fe 系ナノ結晶合金	15－30
スピネル系フェライト	~0

In addition, magnetostriction greatly affects the characteristics of passive components. In other words, in passive components such as transformers and inductors made of soft magnetic materials, when an AC magnetic field is generated by energizing the device, the magnetostrictive characteristics of the magnetic core cause changes in its external dimensions, resulting in mechanical vibration. This causes an increase in abnormal loss (excess loss).

Non-public

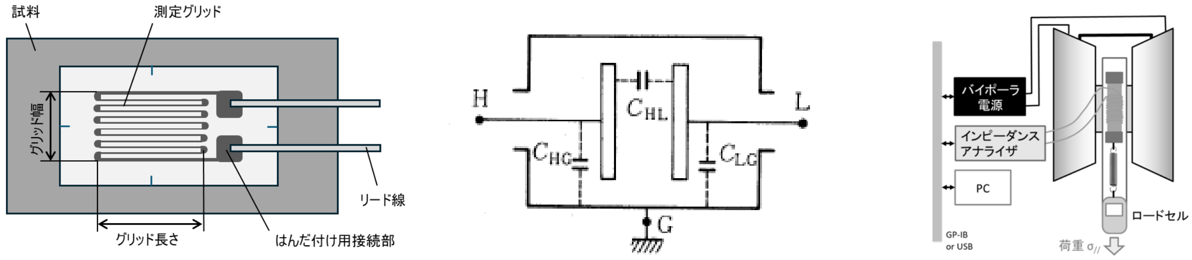
mechanism, as **shown in Figure 5.2.1.** 2, the loss increases when the average of the magnetostriction that exists locally within the nanocrystal grains is not zero but is distributed as the average magnetostriction. Simulations have shown that this is due to the conversion of the magnetostriction energy stored inside the magnetic wall into thermal energy by the lattice vibration caused by the movement of the magnetic wall. It has also been shown that even if the average magnetostriction is zero, the presence of local magnetostriction hinders the magnetic wall movement and increases the anomalous eddy current loss (7)(8). This result suggests that there is a relationship between magnetostriction and loss.

As mentioned above, understanding the relationship between magnetostriction and loss in soft magnetic materials is directly related to the creation of low-loss materials. This means that the creation of low-loss materials is a more urgent issue for soft magnetic materials than that of high saturation magnetic flux density B_s materials.

Non-public

2.1.2 Magnetostriction Measurement

The main magnetostriction measurement methods are the strain gage method, the capacitor method, and the stress-loaded inductance method. The strain gage method (**Figure 5.2.1.3** (a)) is a method for measuring magnetostriction by attaching a strain gage to a sample and measuring the change in electrical resistance of the gage caused by expansion and contraction of the sample. This method is inexpensive and simple, but its disadvantage is that it is difficult to accurately compensate for the reaction to the attachment of the gauges. The capacitor method (**Figure 5.2.1.3** (b)) is a method of measuring magnetostriction from changes in electrical capacitance between a movable electrode and a fixed electrode, which are caused by changes in the position of the movable electrode due to expansion or contraction of the sample (9). This method enables high-precision measurement. The stress-loaded inductance method (**Figure 5.2.1.3** (c)) applies different stresses to one end of the sample and measures the magnetostriction from the magnetic field change caused by the different stresses in the inductance. Although this method is relatively simple and highly accurate, it is difficult to measure fragile samples (10). The target materials of these measurement methods are all bulk or thin strip-shaped materials. Therefore, it is a challenge to develop a method to measure magnetostriction in powder-shaped materials.



(a) (b) (c)

Figure 5.2.1.3 Magnetostriction measurement methods (a) Strain gage method, (b) Capacitor method (three-terminal capacitance method)(9), (c) Stress-loaded inductance method

As mentioned above, magnetostriction is an important magnetic property that cannot be avoided in the development of soft magnetic materials and passive components made of such materials. Future issues include the development of methods for measuring magnetostriction in magnetic powder core materials or fine particles alone, and the understanding of magnetostriction properties in passive components. [Yasushi Endo]

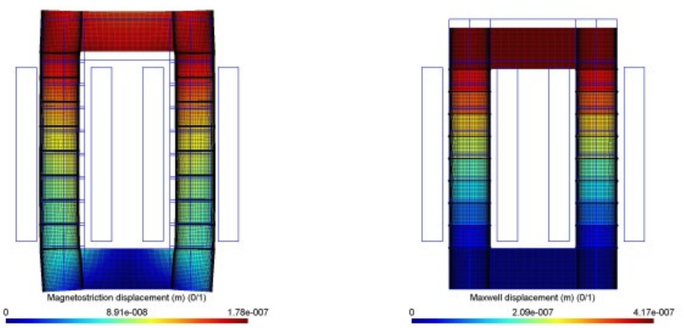
2.1.3 noise

(1) Noise of magnetic components

In power electronics equipment, where efficiency and density are increasing, magnetic components (transformers and inductors) that operate at high frequencies are becoming smaller and more current-efficient. On the other hand, switching operations close to the audible frequency range (20 Hz to 20 kHz) cause magnetic components to vibrate and generate acoustic noises such as "roars" and "squeals" (14). These noises cause degradation of the acoustic quality of the product and discomfort to the user. The following is a brief description of the physical principles of transformer and inductor noise generation, design influencing factors, and control and structural reduction methods.

(2) Cause of sound

The main causes of noise from transformers and inductors are magnetostriction and Maxwell stress, as shown in **Figure 5.2.1.4**(15). In particular, magnetostriction has a component that oscillates at twice the frequency of the magnetic flux during sinusoidal excitation (14). Maxwell stress is caused by the electromagnetic force at the gap and near the windings, which attracts each other between the core fragments and the windings themselves, resulting in structural deformation (15). When these vibrations coincide with structural resonances, they are radiated as sound, resulting in "ringing.



(a) Magnetostriction (b) Maxwell stress

Figure 5.2.1.4 Example analysis of magnetostriction and Maxwell stress in a gapped UU core, Reprinted from [15], © 2015 IEEE

(3) Influence of structure and materials

The structure and materials of transformers and inductors directly affect the noise level and frequency characteristics. As for the magnetic core structure, the toroidal type is relatively quiet because the magnetic path is closed and the electromagnetic stress is easily dispersed. On the other hand, the structure with gaps, such as the E-type and U-type, concentrates electromagnetic forces near the gaps and tends to generate localized vibration (15). Powder magnetic cores with small magnetostriction constants (e.g., Sendust, Fe-Si-Al system) and nanocrystalline alloys are effective as materials to be used (15). Amorphous materials have excellent high-frequency characteristics, but their large magnetostriction may be a source of noise. In addition, designs that suppress the propagation of mechanical vibration by using impregnating resin or buffer materials are also effective (16).

(4) Relationship to circuit operation

The acoustic response of transformers and inductors also strongly depends on the switching waveform of the circuit and the control method: In PWM control, when the switching frequency is within the audible band (around 10 to 20 kHz), second harmonic and side wave band components excite the inductor, resulting in audible noise (17). In burst mode and PFM control, which are employed at light loads, clicks and intermittent sounds associated with periodic switching on and off can be problematic (18). In response to this problem, random PWM and spread spectrum control are used to broaden the tonal noise, in which specific frequency components that are easily perceived as particularly unpleasant by the human ear are dominant, and to make the grating components less noticeable.

(5) Design Methods for Noise Reduction

To reduce transformer and inductor noise, it is important to design the three elements of structure, materials, and control in an integrated manner. Structurally, reinforcement of vibration-prone parts, optimization of gap positions, and suppression of vibration propagation by encapsulating resin are used (16). In terms of materials, selection of low magnetostrictive materials is effective (15)-(19). Control methods include moving the switching frequency out of the audible band, extending the spectrum with diffuse PWM, or controlling the burst interval to a constant high frequency (18). In addition, the finite element method (FEM), which couples magnetic field analysis and structural response analysis, is being used to predict noise sources and evaluate them at the design stage (18)(19).

[Hiroaki Matsumori]

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2.2 Current Status of Mounting Technology and Future Issues

Keyword: Power density, High-density mounting, Three-dimensional mounting, Isolation distance, Heat dissipation, EMI

2.2.1 summary

Power efficiency, volume (or weight) power density, temperature rise due to component heat generation, and noise of power electronics circuits such as inverters and converters are important evaluation indices, and to clear these indices, in addition to improvement of electrical characteristics of each component (e.g., low loss) and circuit design, component mounting is an important technology In order to clear these indicators, in addition to improving the electrical characteristics of each component (e.g., low loss) and circuit design, component mounting is an important technology.

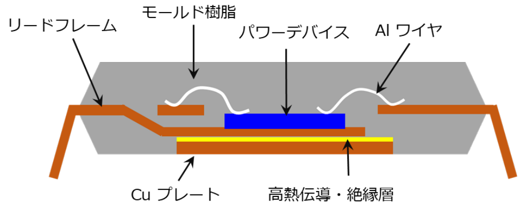
The implementation of power electronics circuits is described in a commentary article by Kashiba [(1)], and the reader is referred to that article for details. In the following, mounting techniques for power devices and passive components in power electronics circuits are described from the viewpoints of high-density mounting, heat dissipation, and noise, and technical issues for improving power density are also discussed.

2.2.2 Mounting technology in power electronics circuits

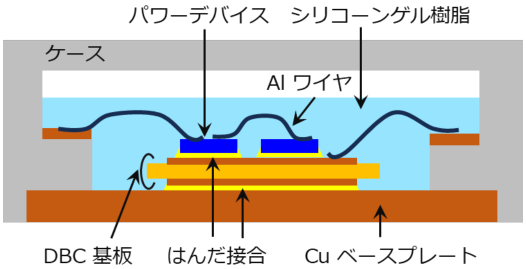
(1) Mounting Technology for Power Devices

a. Power device package

The mounting configuration of power devices can be divided into mold type, case type, and surface mount type. **Figure 5.2.2.1** shows the configuration of the mold and case types. The molded type is used for relatively low current applications. It consists of a power device mounted on a lead frame, Al wire wiring, and molding. The Cu plate at the bottom serves as a heat conductor to the circuit board to ensure heat dissipation performance. The package size has been reduced due to lower power loss and lower thermal resistance in the package as a result of improved performance of power devices. On the other hand, the case type has a structure in which multiple power devices are mounted on a substrate such as a DBC (direct bonded copper) substrate with copper sheets on both sides (two power devices are mounted for high-side and low-side in the half-bridge type often used in power electronics circuits), and then silicone gel To reduce wiring resistance, multiple Al wires are used, but Al ribbons may also be used. The Cu base plate at the bottom serves to dissipate heat from the power devices to the heat sink.



(a) Mold type



(b) Case type

Figure 5.2.2.1 Power device implementation, based on Ref.

Wide bandgap power devices such as SiC and GaN have high-speed switching characteristics, and to suppress voltage surges and ringing during switching, it is essential to reduce the wiring inductance in packages and modules. Low inductance technologies that shorten the wiring length and utilize the negative mutual inductance between adjacent wirings have been adopted [(2)]. SiC and GaN power devices in ultra-low inductance surface-mount packages have been launched for low-voltage applications [(3)(4)].

b. High heat dissipation mounting technology

In recent years, high heat dissipation mounting technology for resin-encapsulated power devices has made great progress, and new structures such as double-sided cooling [(5)], direct water cooling [(6)], and double-sided direct water cooling [(7)] have been developed, leading to the development of compact high-power inverters with direct water-cooled double-sided cooling modules for EVs and PHEVs [(8)].

(2) Passive Device Mounting Technology

a. Capacitors

As shown in **Figure 5.2.2.2**, cylindrical electrolytic capacitors and film capacitors often use insertion mounting, in which the lead terminals of the component are inserted into holes in the circuit board and soldered together, and heat radiation to the circuit board is not expected. Surface-mount capacitors, on the other hand, are in direct contact with the circuit board, thus ensuring a large heat-dissipating area and making them suitable for high-density mounting. In applications with high ripple current, there is concern about temperature rise due to ESR (Equivalent Series Resistance), so heat dissipation is important.

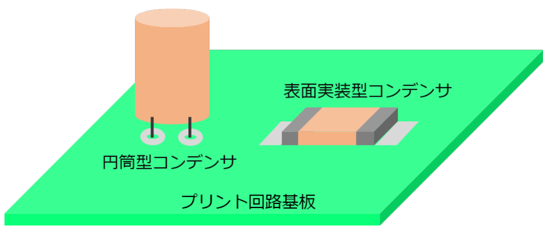


Figure 5.2.2.2 Cylindrical and surface mount capacitors mounted on a circuit board

b. Transformers, inductors

Amorphous and nanocrystalline thin strip-cut magnetic cores, EE and EI type ferrite cores, etc. are used in transformers of isolated power electronics circuits, and heat sinks are sometimes used together to avoid temperature rise due to power loss. A part of the magnetic core is in direct contact with the circuit board, so a certain amount of heat dissipation area can be secured. However, in the case of ferrite core transformers, forced air cooling with a cooling fan is sometimes used because of the risk of thermal runaway at temperatures above 100 ℃. In addition, as **shown in Figure 5.2.2.** 3, a thin EE-type ferrite core planar transformer that uses the inner layer wiring of a multilayer printed circuit board for the windings contributes to thinner power supplies in that it can be integrated with the circuit board, but in an example used in a DC-DC converter module [9], to avoid the effect of temperature rise due to heat generation, the However, in the case of DC-DC converter modules (9), the output power is derated from the rated value according to the ambient temperature, which poses a problem of heat dissipation, and if a heat sink is used to cool the transformer, the advantage of thinness disappears.

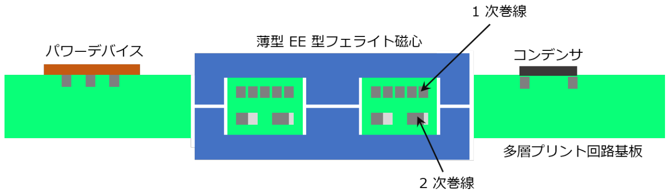
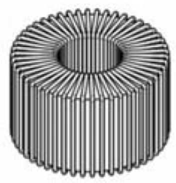
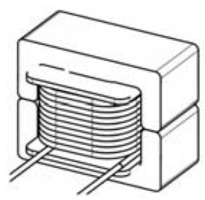


Figure 5.2.2.3 Planar transformer with multilayer printed circuit board and thin EE-type ferrite core

Except for small-capacity high-frequency transformers of MHz or higher used in isolated DC-DC converters for gate circuits of power devices [10], there are almost no surface-mount transformers, and bulk-type transformers make up the majority of transformers, so the progress of transformer mounting technology is slower than that of power devices.

Internal iron core inductors with toroidal cores are mounted either vertically or horizontally to the circuit board, and both are inferior in terms of heat dissipation. On the other hand, EE-type inductors, which are classified as external iron core type, have excellent heat dissipation and are being considered for use in automotive chargers [11]. **Table 5.2.2.1** shows a comparison of toroidal-core inductors and EE-type core inductors.

Table 5.2.2.1 Comparison of toroidal core inductors and EE-type core inductors, based on reference (11)

	toroidal magnetic core	EE type core
Magnetic core shape		
Magnetic core material	Ferrite, Powder Core	
air gap	Magnetic core processing required	Easy gap adjustment
heat dissipation property	be inferior to	Heat dissipation from magnetic core to substrate
winding (coil, armature, etc.)	Directly wound on magnetic core	Easy assembly by using bobbins

Many surface-mount inductors with windings embedded in the magnetic core are now on the market, including those for high-current applications [12].

The implementation of magnetic materials into magnetic cores is described in detail in "Chapter 2, 1.3 Powder Cores and Fine-Particle Composite Cores," etc.

c. Board-integrated components, three-dimensional mounting

Dielectric thin-film capacitors [13] and trench-type capacitors [14] using silicon substrates have been developed as capacitors for substrate built-in or three-dimensional mounting. In particular, trench-type capacitors have the advantage of large capacitance per unit area by arranging many trench structures with high aspect ratio. Both thin-film capacitors and trench capacitors are difficult to increase the withstand voltage and are used exclusively for output smoothing in low-voltage output DC-DC converters with buck converter topology.

There are not many examples of magnetic elements for power electronics circuits built into boards. For inductors for converters with an operating frequency of 1 MHz or higher and an output power of 100 W or less, a micro inductor array (MIA) [15] for three-dimensional mounting and a CMOS [15], and a 3D-mounted converter module in which switches and control system chips are surface-mounted on a PCB with a particulate composite magnetic core inductor embedded in an organic interposer [16].

2.2.3 Technical issues for improving volume (or weight) power density

Compactness and lightweighting of power electronics systems have been continuously promoted in the past. Future technical issues for packaging technology to further promote miniaturization and weight reduction are described below.

(1) Isolation distance

Regarding the isolation distance in power electronics circuits, JIS C 62477-1 specifies the minimum space distance and minimum creepage distance in "Safety requirements for semiconductor power conversion systems and devices" (17), and the higher the operating voltage and frequency, the greater the required isolation distance. In order to improve the volumetric (or weight) power density of power electronics circuits, components must be mounted in high density, which inevitably shortens the distance between components, so it is necessary to determine the component layout and ensure space and creepage isolation by considering the potential difference between components. In particular, it should be noted that the minimum creepage distance exceeds 10 mm for high voltages above 500 V and high-frequency operation above 1 MHz, which restricts high-density mounting of components and limits the improvement of power density by the isolation distance.

(2) Heat dissipation measures

For passive components, surface mount type and planar type have excellent heat dissipation to the air. However, as with power devices, passive components will need to adopt Cu plates as heat conduction paths, and circuit boards will also need to secure heat conduction paths using conductors. Thermal resistance in the heat conduction path is an obstacle to heat conduction, and in particular, the effect of interface thermal resistance between dissimilar materials is significant. To improve the power density of power electronics circuits, it is necessary to determine the component layout based on heat conduction analysis and to optimize component mounting in conjunction with EMI countermeasures, which will be discussed later. It goes without saying that, if power density is increased without improving the power efficiency of the power electronics circuit, the heat generation density will increase and heat dissipation will become difficult, so it is necessary to reduce the loss of the main circuit components in parallel.

(3) EMI countermeasures

a. EMI countermeasures for magnetic elements

High-frequency leakage flux from magnetic elements induces unwanted electromagnetic noise in adjacent elements and wiring, and also leads to losses. A closed magnetic circuit structure with a high permeability magnetic core is advantageous for reducing leakage flux, and is effective for transformers with symmetrical positive-negative excitation operation. However, when the magnetic circuit has an air gap, such as in an inductor for energy storage, leakage flux spreads over a wide space, and the noise generated depends on the placement of components on the circuit board. In the case of gapped inductors, the gap shape is not always the same. In the case of an inductor with a gap, measures such as optimizing the gap shape and localizing the leakage flux are required (see Chapter 2, 1.5 Transformers and Inductors, **Figure 2.1.5.49**).

b. Parasitic inductance and capacitance of power electronics circuits

Parasitic inductance of power device packages and modules is a factor in noise generation as described above. In addition, parasitic inductance of power loop wiring in the main circuit and gate circuit loop of power devices also induces noise due to the switching operation of power devices. Furthermore, electromagnetic field coupling between adjacent components and wiring also generates parasitic components, which also contribute to noise generation. Therefore, in order to improve the power density of power electronics circuits, it is necessary to take EMI countermeasures to reduce noise not only in the layout of components on the circuit board but also in the layout of circuit wiring, and it is desirable to establish a design method based on large-scale electromagnetic field simulations that include the circuit board. [Toshiro Sato]

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2.3 Pioneering the development of iron-nitrogen magnetic cores [1]

Keywords: α''-$Fe_{16}N_2$ powder, oxide film, gas-solid reaction

Next-generation semiconductor devices are the key to higher efficiency and energy conservation in power electronics equipment as a whole [2] [3]. In order to cope with higher operating frequency and switching characteristic control, it is essential to improve the characteristics of inductors, one of the passive components in circuit systems, in the DC to MHz band. Against this background, there is endless interest in how close to the ideal inductors can be fabricated that guarantee soft magnetic properties and excitation response linearity at large amplitudes, and attention has focused on the development of magnetic powder core inductors made of metallic magnetic powder with high saturation magnetization and anti-vortex magnetization.

A well-known metallic magnetic material with high saturation magnetization (σ_S) that can be synthesized from ubiquitous elements is α''-$Fe_{16}N_2$[4][5] , which has a body-centered tetragonal (body-centered cubic (bcc)) structure with N atoms intruding between lattices along the ***c***axis of Fe. (bct)) with body-centered tetragonal (body-centered cubic (bcc)) structure with N atoms intruding between the lattices along the c-axis of Fe. α''-$Fe_{16}N_2$ [4][5] is known. According to previous reports on α''-$Fe_{16}N_2$ powder, values of 200-226 emu/g [6]-[12] have been obtained experimentally as σ_S. On the other hand, the coercive force is as high as several kOe, and no soft magnetic properties have been derived. This is thought to be due to the high uniaxial crystal magnetic anisotropy energy of 9.6×10^6 erg/cm^3 intrinsic to the α''-$Fe_{16}N_2$ phase. In order to use $Fe_{16}N_2$ as a magnetic core material, it is necessary to reduce the crystalline magnetic anisotropy energy. On the other hand, in order to suppress eddy current loss in a magnetic core inductor, it is effective to coat the small-sized metallic magnetic particles with an insulator. The most common insulation coating method is to apply a resin coating to the magnetic powder in a subsequent process, but the coating tends to be thick and non-uniform, and lacks heat resistance.

Considering the above issues, the development of iron nitride soft magnetic powders with high saturation magnetization having ultra-thin uniform insulation film is significant as one of the measures for the development policy of soft magnetic materials for next-generation power electronics inductors. In this section, we introduce an example of synthesis of iron nitride magnetic powder by vapor/solid phase reaction process for the purpose of soft magnetization and formation of ultra-thin film, and also discuss the future development policy of this technology based on the measurement results of iron loss and magnetic permeability of the magnetic powder core made from the synthesized powder. Please note that since the prototype is an inductor, it is not necessarily applicable to transformers.

2.3.1 Synthesis concept of nano-sized iron nitride magnetic powder with insulating film

In general, it is important to ensure the cleanliness of the material surface in a gas-solid reaction. Therefore, as a method to synthesize iron nitride magnetic powder with a film by a series of gas-solid reactions that are not open to the atmosphere, we employed a method in which iron oxide powder is reduced, nitrided, carbonized, and surface oxidized (**Fig. 5.2.3.1**). Co- and Al-containing magnetite of a few microns in size was selected as the raw iron oxide powder. Magnetite was selected from among a number of iron oxides because it contains both Co, an element that enhances saturation magnetization, and Al, an oxidized element for film formation, in the raw powder, which possesses two types of Fe sites of 2 valence and 3 valence is advantageous. This is reduced in a hydrogen gas atmosphere to obtain Fe-Co-Al alloy powder. The reduction reaction is accompanied by a volume reduction due to the removal of oxygen and a crystalline system change from a reverse spinel phase (magnetite) to a body-centered cubic crystalline phase (Fe-based alloys), which is expected to reduce the crystallite size. Then, for the synthesis of the nitride phase and its soft magnetic properties, nitrocarburizing is performed in the lattice by heat treatment in ammonia and acetylene gas atmospheres. Finally, the particles are gently oxidized with dry air diluted with nitrogen gas to form an ultra-thin insulating film on the particle surface. The soft magnetization of bcc-Fe particles by the co-doping of nitrogen and carbon is known in thin films (13), and the sequence of nitriding and carburizing of reduced Fe powder is described in (14).

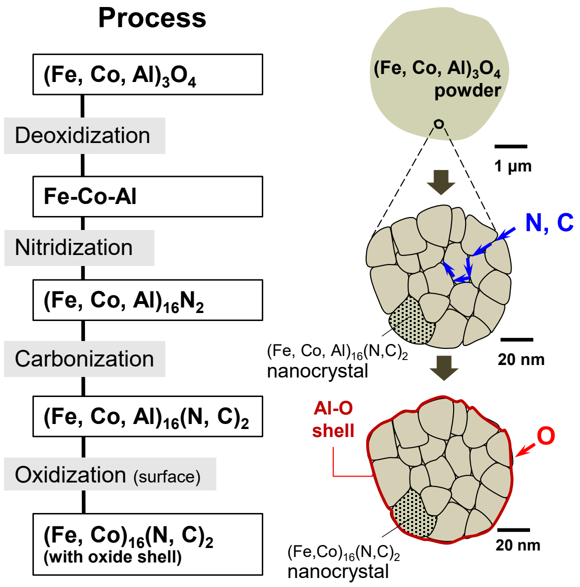

Figure 5.2.3.1 Gas-solid reaction flow and microstructure image of synthesizing iron nitride magnetic powder with

2.3.2 Compatibility between synthesis of ∀α∀ πηασε magnetic powders and film formation

In order to obtain magnetic powder of α''-Fe$_{16}$N$_2$ phase, it is essential to allow nitrogen to penetrate into bcc-Fe particles without forming γ'-Fe$_4$N phase. In fact, it is known that the formation of the γ' phase can be suppressed while the formation of the α'' phase can be promoted by heat-treating the reduced bcc-Fe particles for a long time at a low temperature in an ammonia gas atmosphere of 160 °C to 170 °C. (6)-(12). Therefore, in the verification of the aforementioned concept, it is necessary to examine whether the formation of the α'' phase is possible by allowing nitrogen to penetrate into the reduced Fe-based alloy powder containing Co and Al, and whether the formation of an insulating oxide film of Al is possible by allowing Al to diffuse from within the α'' phase alloy particles to the surface. **Figure 5.2.3.2** shows the XRD profiles **of** magnetic powders synthesized from reduced Fe-based alloy powders containing small amounts of Al and Co, when the oxide film formation process was conducted first (Process A) and when the oxide film formation process was conducted after the nitriding and carbonizing processes (Process B). The XRD profiles of the magnetic powder synthesized by Process A are shown below. The magnetic powder produced by Process A shows only bcc phase formation, indicating that the initial oxide film suppresses the lattice penetration of nitrogen and carbon in the subsequent process. On the other hand, diffraction lines originating from the tetragonal crystal were observed in the sample prepared by Process B, indicating that nitrogen and carbon have penetrated into the magnetic powder. However, if the tetragonal crystal is formed in a single phase, the intensity ratio of the diffraction lines near 51° , bct (101), (011) and bct (110), should be approximately 2:1 due to crystal symmetry , but the diffraction line intensity of the sample from Process B does not reach this ratio. This suggests that the diffraction lines of bcc (110) and bct (110) are superimposed, i.e., that the uncarburized/unnitrided bcc phase remains. In addition, diffraction lines from the γ' phase were also observed, indicating the formation

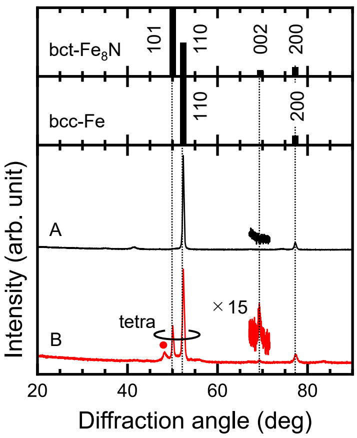

Fig. 5.2.3.2 XRD profiles of magnetic powders of reduced Fe-based alloy powders containing Al and Co when the oxide film formation process was conducted first (Process A) and when the oxide film formation process was conducted after the nitriding/carburizing process (Process B). (Co-Kα source)

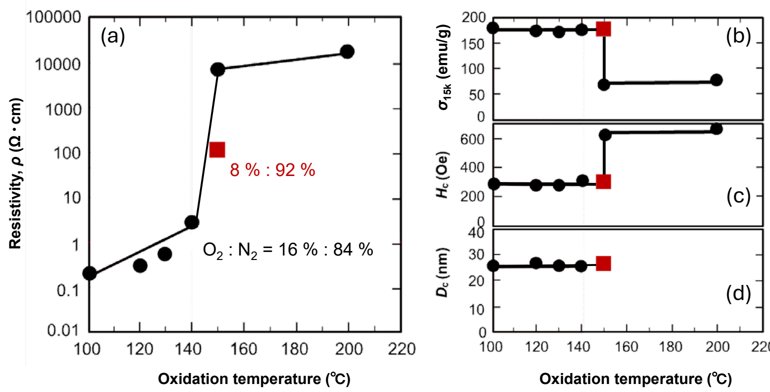

Figure 5.2.3.3 Resistance (ρ), magnetization (σ_{15k}), coercive force (H_c), and crystallite dimensions (D_c) of magnetic powder at 15 kOe applied at different temperatures during the oxide film formation process. Circles and squares indicate the oxygen and nitrogen gas flow ratios during the oxidation process (16 : 84) and (8 : 92),

of a pernitrided/percarbonated phase in the sample. The establishment of a homogeneous gas-solid reaction process at low temperatures for a long time is required. However, the diffraction intensities of the regular lines are weak compared to the background diffraction intensities in the samples examined in this study, so it is not possible to verify whether the nitrogen and carbon intrusion sites are regularized or not. **Figure 5.2.3.3** shows the resistance (ρ), magnetization at 15 kOe (σ_{15k}), coercive force (H_c), and crystallite size (D_c) of the magnetic powder when the temperature of the last oxide film formation process is varied among the processes shown in **Figure 5.2.3.1** The temperature of oxidation was increased from 140 °C to 160 °C. When the oxidation temperature is increased from 140 °C to 160 °C, the resistance increases by three orders of magnitude and σ_{15k} is reduced by half, indicating that the magnetic powder is oxidized in this temperature range. Therefore, it can be inferred that magnetic powder with an ultra-thin oxide film, i.e., magnetic powder with an ultra-thin oxide film, can be formed by oxidizing at a temperature of about 140 °C, where signs begin to appear, with a resistance one order of magnitude higher than that of alloy powder but without much decrease in saturation magnetization.

2.3.3 Fabrication and Excitation Characteristics of Powder Core

Figure 5.2.3.4 shows the magnetization curves of the iron nitride magnetic powder used in the fabrication of this magnetic powder core. (a) shows the entire magnetization curve and (b) shows the expanded curve near the origin. The coercive force was 473 Oe, which was considerably higher than the 100 Oe that had been obtained by using a small amount of raw powder under nitriding and carbonizing conditions. This is thought to be due to the fact that the amount of starting powder in the raw material storage container was increased to obtain the 2.5 g of iron nitride alloy powder with coating required to fabricate the magnetic core, and that uneven reactions caused by batch processing with several containers lined up in the reaction furnace resulted in variations in the properties. The iron nitride magnetic powder was compacted as follows. First, 2.5 g of magnetic powder was mixed with approximately 0.2 g of binder (phenol resin). Next, this mixture was filled into a mold with an outer diameter of 13 mm and an inner diameter of 8 mm, and formed into a toroidal shape with a height of approximately 6 mm at 10 ton/cm^2. Finally, the toroidal molded product

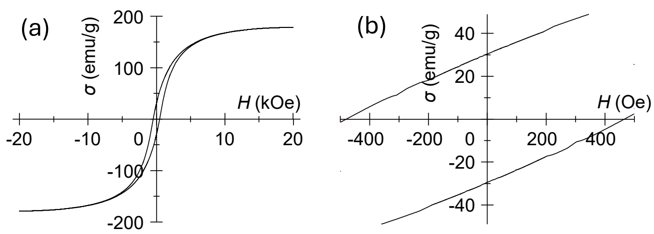

Figure 5.2.3.4 (a) Magnetization curve of magnetic powder prepared at an oxidation temperature of 140° C (b) Enlarged magnetization curve near its origin

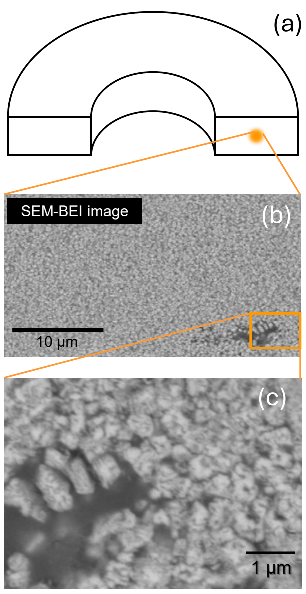

Figure 5.2.3.5 Results of observation of microstructure of iron nitride-based magnetic powder core by SEM reflection electron image (a) Observed area (b)

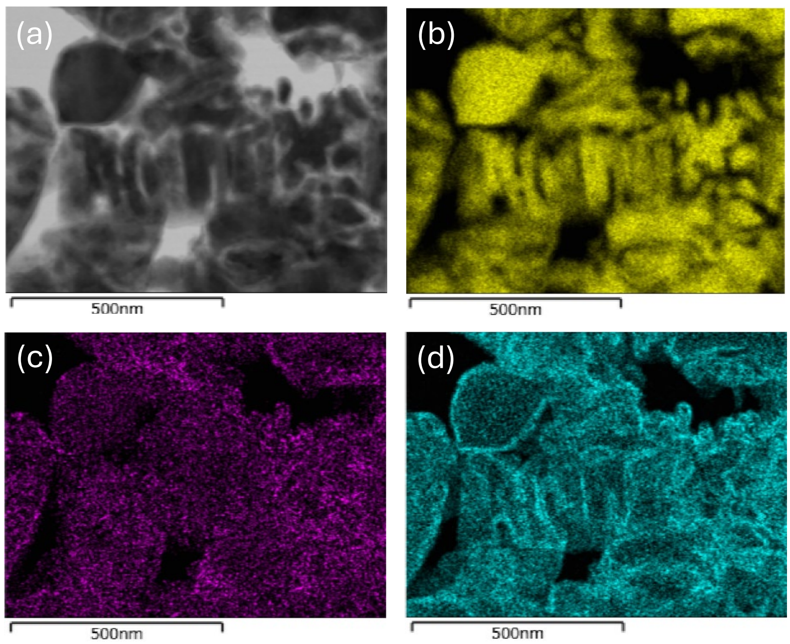

Figure 5.2.3.6 Results of STEM observation of the microstructure near the center of the cross section of an iron nitride-based magnetic powder core (a): bright-field image (b), (c), (d): characteristic X-ray maps of Fe, Al, and O

was heated at 150 °C for 45 minutes to bond the powder and phenolic resin.

The results of observation and analysis of the microstructure around the center of the cross section of the core of the iron nitride-based magnetic powder core produced in this study are shown in **Figures 5.2.3.5** (scanning electron microscope: SEM) and **5.2.3.6** (scanning transmission electron microscope: STEM). In the STEM observation, (a) shows the bright-field image, and (b), (c), and (d) show the characteristic X-ray images of Fe, Al, and O in the same field of view as (a). The O and Al are unevenly distributed with a thickness of nm outside the rich Fe region, indicating that an Al oxide film was formed on the outside of all magnetic particles in the field of view, and that no plastic deformation occurred during the compacting process. **Figure 5.2.3.7** shows the excitation characteristics ((a) iron loss P_{cv}, (b) and (c) effective complex permeability real part μ' and imaginary part μ'') are shown as contour plots for the excitation amplitude (B_{ex}) and excitation frequency (f_{ex}). For comparison, (d), (e), and (f) also show the excitation characteristics of a toroidal magnetic powder core similarly prepared using a commercial sendust alloy powder (Sanyo Special Steel Co., Ltd., average grain size 2 μm). For the sendust core, the μ' shows a large value of about 81 regardless of the excitation conditions. Pcv increases with increasing f_{ex} and B_{ex}, reaching 1236 kW/m^3 under the excitation condition of (f_{ex}, B_{ex}) = (2 MHz, 20 mT). On the other hand, in the iron nitride-based pressed powder core fabricated in this study, μ' depends not only on f_{ex} but also on B_{ex}, and the magnitudes of μ' and μ'' are one order of magnitude smaller than those of Fe-Si-P_{cv} shows the same trend as the Fe-Si-Al core, but its value is one order of magnitude larger, reaching a magnitude of 24,590 kW/m^3 under the excitation condition of (f_{ex}, B_{ex}) = (2 MHz, 20 mT). These results mean that the soft magnetic properties of the iron nitride-based core are not yet at a stage where they can be compared with those of practical materials.

2.3.4 view

Iron nitride magnetic powder with an insulating oxide film was synthesized from magnetite-based starting powder by a series of gas-solid reaction processes not open to the atmosphere, and a toroidal-shaped magnetic powder core was fabricated using this magnetic powder. The advantage of this synthesis method is that it is relatively easy to achieve nitrocarburizing, carburizing, and oxide film formation on magnetic particles of several tens to several hundred nm in size during the process. Of particular note regarding nitriding and carburizing is that the reaction proceeds even with alloys containing film-forming elements (in this instance, Fe containing trace amounts of Al); furthermore, regarding film formation, a uniform coating with a thickness on the order of a single nanometer is applied to the exterior of all magnetic particles through a low-temperature treatment of only about 140 °C. On the other hand, the process conditions for each gas-solid reaction are severe, and it is essential to ensure process uniformity, especially when synthesizing large quantities of magnetic powder under the same conditions. From this point of view, the reaction furnace is important, and it is expected that the sample rotation type kiln furnace will be adopted instead of the fixed sample batch type furnace, which is the sample preparation furnace introduced in this paper.

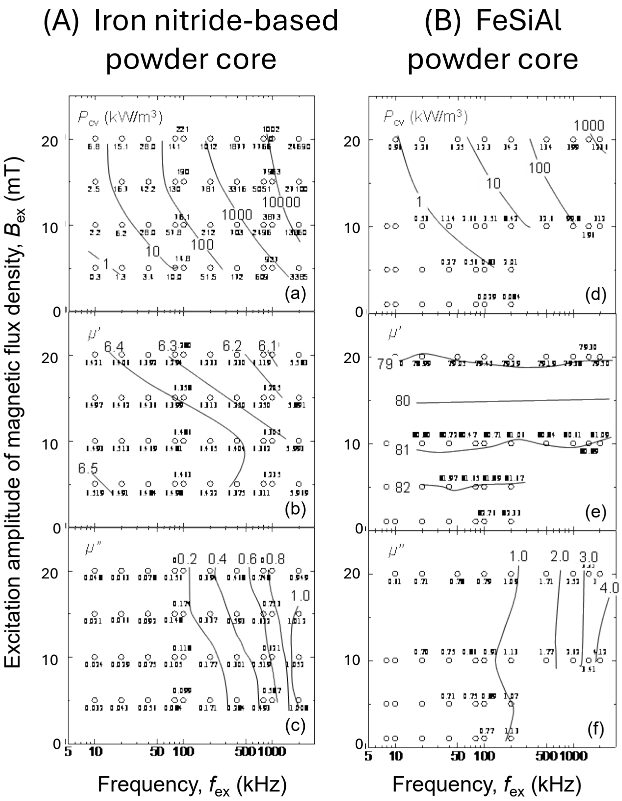

Figure 5.2.3.7 Contour plots of excitation characteristics ((a) iron loss P_{cv}, (b) and (c) real and imaginary parts of effective complex permeability μ' and μ'') of (A) an iron nitride-based core and (B) a FeSiAl core against excitation

In order to realize a near-ideal inductor, it is necessary to achieve some degree of soft magnetic properties and linearity of excitation response at large amplitudes, and the iron nitride-based magnetic powder synthesized in this study was insufficient from this perspective. We applied the method of" reduction of uniaxial crystal magnetic anisotropy energy in the α'' phase by co-doping nitrogen and carbon," which has been achieved in thin films, to the powder, but we assume that the substitution of nitrogen for carbon was not sufficient in the powder. Recently, a research group at the University of Minnesota has developed a method called "minnealloy," in which floating dissolved Fe with urea is rapidly solidified and heat-treated to transform the γ' phase into the α' or α'' The method of transforming the floating dissolved Fe with urea into the"minnealloy" phase [15] and the method of carbonitriding bcc-Fe by making a rapid-cooled Fe-C thin strip by the melt-spinning method and nitriding it in an ammonia atmosphere (16) have been reported. Although neither of these methods has produced a single-phase sample of α' or α'' phase, they are noteworthy as bulk methods that can achieve both high saturation magnetization and good soft magnetic properties. In the above, we have described a strategy to reduce the intrinsic crystalline magnetic anisotropy during soft magnetization. In addition to these measures, it may be effective to utilize the nanocrystal effect, i.e., to increase the contact grain boundary area by clustering nanocrystals with different crystal axes into tens of nm in size, and to increase the intergrain exchange coupling dominantly while canceling the magnetocrystalline anisotropic energy.

[Shin Saito]

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2.4 Recycle and Reuse

Keywords：recycling, reuse, life cycle assessment

2.4.1 Introduction.

Power electronics technology plays a key role in improving energy efficiency and introducing renewable energy, and plays an indispensable role in combating climate change [(1)]. In recent years, however, attention has also focused on the environmental impact associated with the manufacture, use, and disposal of power converters themselves [(2)]. Traditionally, emphasis has been placed on power conversion efficiency (%) and power density (kW/m^3) as performance indicators, but sustainable power conversion systems are required to reduce environmental impact (e.g., greenhouse gas emissions and resource consumption) throughout the product life cycle. Life cycle assessment (LCA), which quantitatively evaluates the environmental impact of products and technologies, is an effective method for this purpose. In recent years, an approach that integrates LCA into the design phase to design and optimize products with consideration of environmental impacts has been attracting attention in the field of power electronics. This section focuses on examples of environmental impact, integration of LCA into the product design phase, and utilization of multi-objective optimization (energy efficiency, material efficiency, greenhouse gas emissions, etc.). Energy Efficiency is Not Enough!" [(2)] published in the IEEE Power Electronics Magazin will be mainly referenced and the case studies will be introduced as well as LCA utilization by major companies, eco-design (environmentally conscious design), and the paper also summarizes recent efforts and presentations on the promotion of LCA, eco-design, and the circular economy by major companies, and discusses the connection between research and industrial trends.

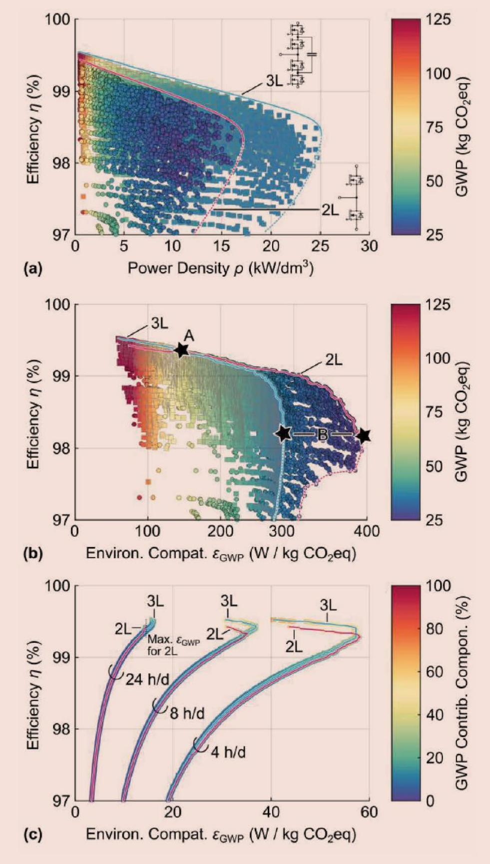

Figure 5.2.4.2 Energy efficiency vs. environmental compatibility index (ε_{GWP}) for different circuit configurations (number of levels) of power converters

2.4.2 Research Trends

Recent studies have applied LCA to the environmental load of power electronic equipment and discussed design tradeoffs that cannot be captured by conventional energy efficiency indices alone. Reference [(1)] suggests that "energy efficiency alone is not sufficient" and that it is necessary to incorporate environmental load as a new performance indicator in design optimization. In this study, using a 10 kW-class power electronics circuit as an example, carbon emissions during product manufacturing (Global Warming Potential, GWP) and emissions due to energy loss during operation are evaluated in an integrated manner. The results show that in a scenario with a low-carbon future power grid, a design that emphasizes GWP reduction during initial manufacturing has a higher environmental impact over the entire life cycle than a design that maximizes conversion efficiency to reduce CO_2 emissions in the use phase. In other words, the cleaner the power, the less "highest efficiency = best". Similarly, for devices that are used for short periods of time (e.g., smartphone chargers used for only about one hour per day), designs with lower environmental impact at the time of manufacture are more advantageous overall, even if the efficiency is slightly lower.

Figure 5.2.4. 1shows the relationship between energy efficiency and environmental compatibility index (ε_{GWP}) for power converter design. Here, **Figure 5.2.4.1** (a) shows the relationship between efficiency and power density, **Figure 5.2.4.1** (b) compares the GWP of each design when the use phase (10 years, 8 hours/day operation) is considered, and **Figure 5.2.4.1** (c) shows the Pareto front between efficiency - environmental compatibility index (ε_{GWP}) under different power supply scenarios respectively. **Figure 5.2.4.1 shows** that the high-efficiency design (A) may have a long-term advantage in total GWP over the low-efficiency/low-GWP design (B), even if the initial GWP is large. In other words, the advantage of pursuing maximum efficiency will decrease and the importance of GWP reduction will increase in future low-carbon power generation. Furthermore, in reference [(1),] in an attempt to integrate environmental impact indicators into the design phase, LCA was incorporated into the conventional optimization problem to perform multi-objective optimization of efficiency, power density, and environmental impact. In that method, environmental footprint data for various components are used to estimate the environmental impact over the entire life cycle for each design, and the relationship with other performance indicators such as efficiency is analyzed. In **Figure 5.2.4.2**, a study comparing two-level (2L) and three-level (3L) inverter circuit configurations reveals that the 3L method is superior in terms of power conversion efficiency and power density, but has a higher GWP at the manufacturing stage due to the increased number of semiconductor elements, and depending on the operating conditions, it is lower than the 2L method in ε_{GWP}. Specifically, the 2L system with

fewer components has a smaller life-cycle environmental impact (i.e., the maximum value of ε_{GWP} is larger) in an environment of 4 hours of use per day, but the 3L system with higher efficiency is more advantageous in an environment of continuous use of 8 hours or more, indicating that the optimal design solution depends on operating conditions. This can be said to be an introduction of the environmental load version into the concept of total cost of ownership (TCO), which looks at the compromise between initial cost and operating cost. Furthermore, many researchers have pointed out the importance of assessing the impact of environmental impacts not only in terms of a single indicator (e.g., CO_2 emissions) but also in terms of multiple environmental impact categories (resource consumption, ecosystem impacts, human health impacts, etc.) using the internationally widely used ReCiPe 2016 method as well as GWP (climate change impacts). human health impacts, etc.), and shows that different trends emerge for each category depending on the design.

In addition to this, there are reports of LCA for the manufacturing processes of wide bandgap semiconductor devices such as GaN and SiC, comparing their environmental impact with that of conventional Si devices and analyzing them during the manufacturing process. Reference (3) reported the first comprehensive LCA for GaN-on-Si power devices, and showed that power and clean room demand, PFC gas emissions, precious metal use (e.g., gold), and organic solvent use in the manufacturing process were the main causes of environmental impact. In addition, a comparison of Si, GaN, and SiC devices indicated that while wide bandgap devices have great potential for higher efficiency in the use stage, the environmental impact of the manufacturing stage is not negligible.

These studies quantitatively evaluate the "relationship between energy efficiency improvement and environmental impact during manufacturing" when introducing new materials and technologies, and promote the selection of truly sustainable technologies. In addition, research to enhance circularity, such as durability and ease of reuse/recycling, in the design stage of electrical and electronic equipment is progressing in response to the Ecodesign Directive and circular economy policies, mainly in Europe. For example, standardization studies on material efficiency and circular economy of motor drive systems have been reported in preparation for the formulation of the European Commission's eco-design regulations (3), and guidelines for "Design for Circularity" in the electrical and electronics industries and review studies that summarize trends in the industry as a whole have also appeared. And review studies that organize industry-wide trends have also appeared (4)(5). These provide product design guidelines from the perspective of LCA, and specific design strategies are discussed, such as expanding reuse opportunities through modularization of parts and improving resource recoverability at the end of product life. In general, as a research trend after 2020, there is a noticeable trend to elevate LCA from an "ex-post evaluation tool" to a "proactive design decision-making tool. While the main application of LCA has been to evaluate and report environmental impacts after product development, there is now a shift toward utilizing LCA for more comprehensive optimization and design trade-off studies by considering environmental impacts in parallel with other performance factors from the early stages of development. The accuracy and consistency of environmental data for each component has been pointed out as an issue in this process, and researchers have called for "the development of a reliable database on the environmental footprint of components" and "smart data sheets that include information on environmental impact. In fact, detailed design-stage LCAs (so-called a priori LCAs) currently tend to be highly uncertain due to lack of data. Therefore, data sharing and standardization in the research community and industry as a whole, as well as the development of efficient estimation methods, are considered important issues for the future.

2.4.3 Corporate Trends and Practices

In response to the progress of research, the industrial world has been active in efforts to reduce the life cycle environmental impact of power electronics products and to promote a circular economy. Here we review recent developments at Infineon, ABB, Siemens, and Mitsubishi Electric.

(1) Infineon Technologies (6)(7)

Infineon is actively working to improve the environmental performance of its products and build a recycling-oriented business model. The company is committed to reducing the environmental impact of its products throughout their lifecycles, and has set targets for calculating and reducing the CO_2 footprint of its manufacturing processes. For example, the company is implementing programs to reduce energy use and greenhouse gas emissions during manufacturing, disclosing information on the composition of materials used in its products, providing information to recyclers, and ensuring that hazardous substances are not used. Furthermore, the 6R concept of circular economy (Reduce, Reuse, Repair, Refurbish, Recycle, Reliability) is incorporated into product design and operation. As a concrete example, the company supports product repair and reuse by utilizing electronic component authentication technology to verify the authenticity of replacement parts, thereby contributing to compliance with the "right to repair" regulations that are evolving in Europe and extending product life. Infineon is also involved in joint research projects in Europe to improve the materials cycle and recycling processes for electronic devices, with the aim of reducing electronic waste and building a sustainable supply chain. Infineon has shown its policy that semiconductor products not only contribute to reducing energy consumption but also take responsibility for their environmental impact from manufacturing to disposal, and has incorporated LCA and eco-design methods into its business strategy.

(2) ABB [8]

ABB is actively introducing LCA and Environmental Product Declarations (EPDs) to objectively demonstrate the environmental impact of its products and solutions. The company has a strategy to recycle resources at every stage of the product life cycle (design, procurement, manufacturing, use, and disposal). As a specific initiative, the company has developed a product certification program called EcoSolutions, which certifies more than 20 product lines that meet circularity criteria. These certified products are given an Environmental Product Declaration (EPD) in line with ISO standards, and third-party verified life cycle environmental data is made public. Such efforts to improve transparency are not only aimed at improving the environmental impact of the company's products, but also at helping customers to consider the impact of their environmental impact when selecting equipment to install. In addition, as a contribution to a low-carbon society, the company is reviewing its procurement of raw materials. For example, in cooperation with Boliden of Sweden, the company is attempting to reduce CO_2 emissions by an average of 200 kg per unit by switching to low-carbon footprint copper for its electric motors and stirring devices. Similarly, by using recycled steel scrap from blast furnaces and recycled plastic materials, they have reported a reduction of several tens of percent in the manufacturing stage emissions of electric power equipment. In addition, new products such as synchronous reluctance motors have achieved both high efficiency and non-use of rare materials (e.g., rare earth magnets), thereby extending product life and making them easier to recycle. In this way, the company is working to reduce its environmental impact and shift to a circular economy through design improvements based on LCA data and supply chain reforms.

(3) Siemens [9]

Siemens has positioned eco-design as a pillar of its corporate strategy and has incorporated sustainability criteria into its product development process. Later, it will be expanded to software and services. The eco-design approach focuses on three areas: responsible product development (applying eco-design at the development stage), clean supply chain (using recycled resources and reducing hazardous substances), and improving efficiency at the company's sites (energy conservation and waste reduction at production sites). In the product development process, the company conducts LCA on representative models of major products in each business unit, and has a system in place to feed the results back into the setting of performance targets for environmental impact and design improvements. Specifically, the "carbon footprint (CO_2 emissions from manufacturing to disposal)" of each product is calculated and disclosed as EPDs internally and externally as necessary, and improvement measures such as changes in materials, energy efficiency, and modular design are implemented using the knowledge obtained. The company emphasizes that such LCA-driven design optimization can achieve both cost reduction and environmental impact reduction for both the company and its customers. For example, the long-term use model through product remanufacturing, leasing, and servicing can lead to new revenue opportunities while reducing raw material procurement and disposal costs. In addition, the company is promoting standardization and data sharing in cooperation with suppliers and industry associations, and is developing a platform called "EcoTransparency" to seamlessly communicate product environmental information to end users (an attempt to connect LCA models for each product and dynamically calculate its footprint). As these efforts suggest, the company is adopting a strategy to incorporate LCA into its management and technological development decision-making and to convert environmental impact into competitiveness.

(4) Mitsubishi Electric [10]

As **shown in Figure 5.2.4.3**, Mitsubishi Electric is also promoting design through "visualization" of the life cycle CO_2 emissions of its products. The e-Pro system, an in-house system that centrally manages environmental load data, has been built to automatically calculate and tabulate the life cycle CO_2 emissions (LC-CO_2) of each product by entering the annual energy consumption, product mass (by material), and shipping destination information for each product. This system enables us to quickly perform LCA-equivalent evaluations of many products and to disclose necessary environmental information internally and externally. In addition, each product group sets its own carbon neutrality and circular economy targets for 2030 and 2050, and the environmental load data of each product obtained by e-Pro is fed back to the design department to promote eco-design (environmentally conscious design). For example, the PDCA cycle is constructed so that if the CO_2 emissions at the manufacturing stage of a product are high, a review of materials and improvement of the manufacturing process are considered, and if the energy consumption at the usage stage is high, energy-saving functions are enhanced and operational proposals are made. In addition, the company is now able to efficiently respond to external requests for environmental load data (inquiries from customers and regulatory authorities), and has also been effective in acquiring third-party certification (such as Energy Star) and green procurement. In addition, to respond to the circular economy, the company is focusing on extending the service life of its products and recycling resources. For example, the company has set an internal target of 100% effective utilization of plastic waste (by FY2036), and is promoting visualization

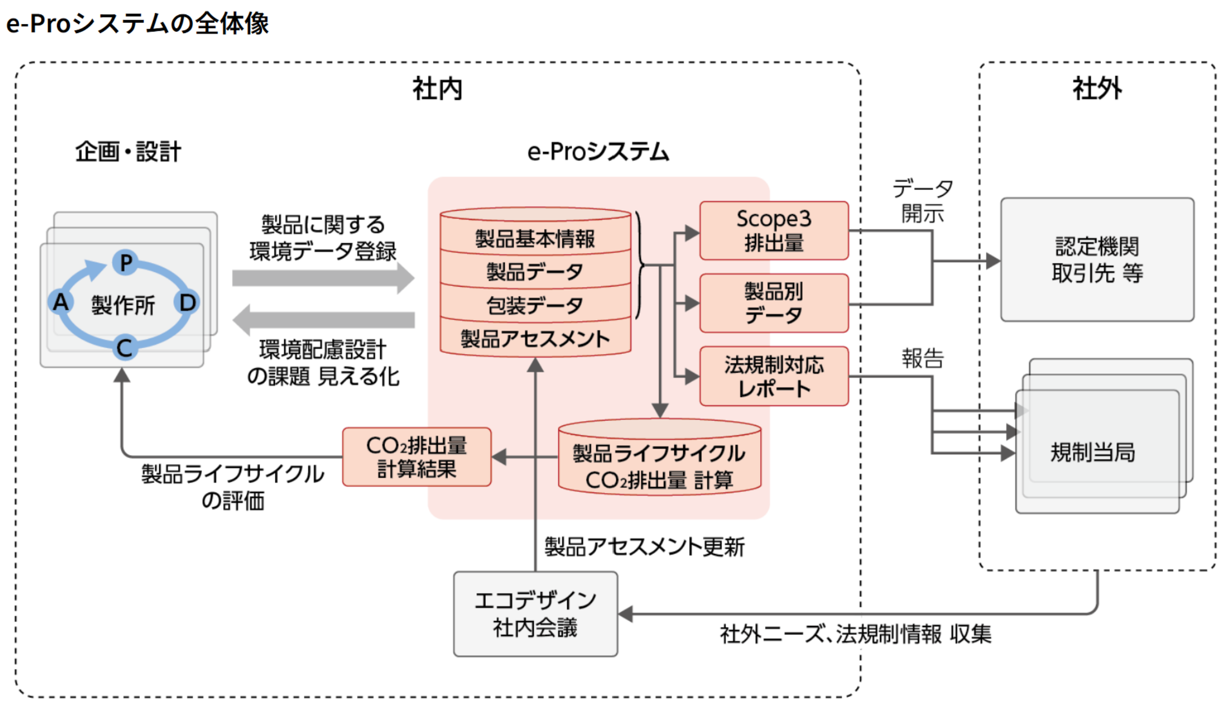

Figure 5.2.4.3 Overview of Mitsubishi Electric's e-Pro environmental load data management system

and reduction of waste plastic emission sources and collaboration with recycling companies at each plant. In this way, the company is developing initiatives to achieve consistent environmental impact reduction from design to disposal through its self-developed LCA management system and systematic target setting.

2.4.4 Life cycle and CO_2 assessment for motors [11]

The current status of recycling and reuse of motors and their peripheral materials was reported based on the symposium "Evaluation of CO_2 in the Life Cycle of Motors" at the 2025 IEEJ National Convention.

In Japan, JAMA (Japan Automobile Manufacturers Association, Inc.) has revised its LCA guideline, setting a standard intensity by dividing the material manufacturing stage into upper and lower processes, introducing energy-based calculation in addition to the conventional weight-based calculation, and indicating a policy to evaluate the deduction of disposal and recycling stages using CFP (carbon footprint). The standard is becoming more sophisticated with a view to international harmonization. These trends strongly encourage the simultaneous promotion of improvements and disclosures based on quantitative evidence in each process of design, procurement, manufacturing, and recovery of electrified products including motors.

CO_2 intensity by material clearly shows the issues that have a large impact in practice. For the electromagnetic steel sheet, an average value of approximately 2.3 tons CO_2 per ton of steel is shown, and approximately 80% of this is derived from the pig iron making process using a blast furnace. In other words, the expansion of the electric furnace ratio and the future development of hydrogen steelmaking will affect the CFP of the manufacturing stage of motor iron cores. Data on the energy balance by process confirm the dominance of the reduction process. For copper and magnet wire, a typical value of about 3.10 kg-CO_2 per kg of wire is shown, with a significant contribution from the front-end process from electrolytic copper to wire rod. Winding wire has a high share in the motor material inventory, and the selection of winding material, yield, and improvement of process efficiency such as coating and baking provide room for reduction in the manufacturing stage. In the case of aluminum, the amount of new ingot used in Japan is about 12 kg-CO_2/kg, 80% of which is accounted for by electrolytic refining, or electricity. On the other hand, green aluminum is about 4 kg-CO_2/kg, and recycled ingots are about 0.4 kg-CO_2/kg, showing a 97% reduction compared to new ingots, and the designation of recycled materials and materials derived from low-carbon electricity is the most effective measure in the procurement of materials for motor housings. However, the lack of a domestic resource circulation system and the overseas flow of scrap have become apparent as problems, and a circular supply network design is indispensable. For rare earth permanent magnets, the current assumed value is about 40 kg-CO_2/kg. Standardization is being promoted because the calculation results are greatly influenced by the drafting method of the refining process and the difference in processing yield depending on the shape of the product. Magnets are the impact driver of the motor manufacturing stage, and the key is to design with disassembly, recovery, and reuse in mind and traceability in the supply chain.

As LCA findings by application, for industrial 2.2 kW class motors, CO_2 emissions in the use phase account for the latter half of 90% of the total, and PMSM (permanent magnet motor) with the highest efficiency has the lowest life cycle emissions. The evaluation formula is presented in the form based on motor output, efficiency, time of use, and power coefficient. Using the CO_2/kWh coefficient of 0.40 to 0.42 in Japan, PMSM is the smallest and IM (induction motor) is the largest.

A scenario has been proposed in which the CO_2 emission coefficient per kWh in Japan is reduced by about 45% from the FY2020 level. The decarbonization of power sources may weaken the dominance of the use stage and push up the relative importance of the manufacturing stage and material selection. Therefore, an optimal design with the future coefficient as a parameter, i.e., a design theory that simultaneously optimizes efficiency, material CO_2, and ease of recycling, is needed.

In the case study of the air-conditioning field, a framework for calculating CO_2 during manufacturing from the material inventory is presented for IPMSM for compressors and motors for fans. The composition of outdoor and indoor units and the motor type for each model are organized, and the contribution of each material is evaluated in line with the actual system configuration.

From the above, optimization of "material designation and procurement" is effective in the short term for the promotion of recycling and reuse in the power electronics field. Specifically, the adoption of recycled ingots and green aluminum should be positioned as a standard for aluminum, material CO_2 intensity should be specified in parts management and thoroughly controlled at the design stage, and electromagnetic steel sheets should be switched from blast furnace materials to electric furnace materials and their substitutability should be evaluated assuming future trends in hydrogen steel production. Permanent magnets are still in the process of being standardized, and the development of structures and processes based on the assumption of disassembly and recovery, as well as traceable data management, are critically important in terms of both uncertainty reduction in the manufacturing stage and resource recycling.

In the mid- to long-term, a data linkage mechanism that can withstand regulatory and market demands, i.e., a CFP platform integrated into the workflow of design, procurement, manufacturing, and recovery, and a system to consistently manage specific energy consumption by upper and lower processes, energy-based calculation, and deduction evaluation using CFF is required. This will make it possible to present a design method (efficiency x material CO_2 recyclability) that incorporates future values of power coefficients for each individual model and market, and to link CO_2 coefficient reduction on the policy side and design optimization on the corporate side. emissions in the use stage are dominant in the recycling and reuse of the motor field, but there is a phase in which reductions in the manufacturing stage are steadily accumulated through material selection and design changes. The three pillars are reduction at the use stage through efficiency improvement, procurement of recycled aluminum and low-carbon materials, and standardization of magnets and design based on the assumption of recovery. As the decarbonization of electric power continues to progress, the importance of the manufacturing stage will increase. Therefore, the realization of design guidelines that incorporate higher resolution of CFP, data linkage, and ease of disassembly and recovery will directly lead to the realization of carbon neutrality for the entire power electronics industry.

2.4.5 Considerations and Future Issues

As described above, many companies are rethinking their product design, manufacturing, and services using LCA methods and environmental data to shift to a decarbonized and circular business model; Infineon is focusing on the manufacturing phase of its devices, but is also taking steps to improve circularity at the device's end; ABB and Siemens are leading the way in greening the market by integrating eco-design across their broad product portfolios and providing LCA-based environmental information to their customers. Mitsubishi Electric also shares the same trend of "visualization of environmental impacts" and "integration into the design and supply chain" throughout the industry.

Based on recent research and corporate practice, it can be said that the use of LCA in the power electronics field has entered a new phase. This is a paradigm shift from a mere ex-post evaluation of environmental impact to a paradigm in which environmental impact reduction is positioned as one of the design goals. This trend is symbolized by the statement "Energy Efficiency is Not Enough!". As the room for improvement in energy conversion efficiency is becoming smaller, the environmental impact of products (e.g., CO_2 emissions and resource consumption per unit output) is being closely examined as the next performance index (1). In research, incorporating environmental load into multi-objective optimization has led to the discovery of new trade-offs and the search for design solutions. On the other hand, in the corporate world, product development and environmental information disclosure based on LCA data have become important for competitiveness and compliance (6)(9). However, many issues remain to be overcome in order to further advance this trend.

The first is data reliability and standardization. Environmental impact data on component materials and manufacturing processes are necessary for rapid and accurate LCA at the design stage, but currently available data may be difficult to compare due to variations among sources. For this reason, researchers have proposed the importance of standardization of LCA methods and databases, as well as provision of environmental data by suppliers (e.g., addition of environmental impact items to "smart data sheets") (2)(6). The establishment of reliable databases through cross-industry collaboration could serve as a foundation for the future.

Second, it is important to deal with trade-offs in design decisions that consider the entire product life cycle. The dilemma is that the pursuit of higher efficiency and performance increases the number and complexity of components, which in turn increases the burden and difficulty of repair in the manufacturing and disposal stages. For example, while high integration and miniaturization of power converters offer significant advantages in operation, they also make disassembly, repair, and recycling more difficult. Therefore, the challenge is how to balance long life and modularization with performance optimization. In the future, "design based on reuse and repair" and "predictive maintenance technology to extend product life" will become increasingly important, and comprehensive studies, including integration with reliability engineering and maintenance technology, will be necessary. In addition, reduction of hazardous waste and recovery of scarce resources should also be considered in the post-use stage, and these are interdisciplinary issues that differ from conventional power conversion circuit design.

Third, the development of design support tools and decision-making processes is also an issue. Evaluating a large number of design candidates in multi-domain optimization is computationally demanding, and interpretation of the results is complex. In recent years, the application of AI technology and design automation have progressed, and methods for finding promising solutions from large databases have emerged (2). In future design environments, it is expected that electrical performance and environmental load will be simultaneously evaluated on an optimization platform incorporating AI, and designers will be able to visualize the tradeoffs in real time. In fact, the integration of digital engineering and LCA is progressing, as evidenced by the product carbon footprint calculation tools that Siemens and others have begun to offer and the integration of LCA modules into various CAD/CAE software (9).

In order for engineers to design products with reduced environmental impact, they must have an understanding of LCA and sustainability in addition to conventional electrical engineering knowledge. It is essential to establish a system in which not only the product development department but also the procurement, production, and service departments work together to solve problems from a life cycle perspective in order to realize products with a truly low environmental impact (10).

In light of the above, the power electronics field is approaching what can be called the next stage of development. In other words, this is the stage where, following advances in semiconductor technology and performance improvements through innovative topologies, environmental impact and circular economy will become the new axis of competition. In order to make this transition successful, academia, industry, and standardization organizations must collaborate to share data and knowledge, and accumulate comprehensive optimization methods and practical knowledge. While maintaining the original mission of power electronics technology - namely, effective utilization of energy and innovation of power infrastructure - constant improvement and innovation are expected to ensure the sustainability of the technological foundation itself. The power electronics technology is expected to continue to improve and innovate so that the technological foundation itself will be sustainable.

[Keiji Wada]

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2.5 rare material

Keyword: Rare material functionality, High-performance soft magnetic materials, Global market trend

2.5.1 Introduction.

Rare materials play an extremely important role in improving the basic properties of the soft magnetic materials that make up magnetic elements. Typical rare materials include boron (B), niobium (Nb), cobalt (Co), vanadium (V), zirconium (Zr), and molybdenum (Mo). The addition of these rare materials to soft magnetic materials significantly improves mechanical and magnetic properties, as well as structural stability and microstructure control during heat treatment. As a result, it is possible to develop highly efficient, compact, and thermally stable magnetic elements that are indispensable for power electronics. In addition, with increasing global demand for electrification, miniaturization, and sustainability, supply chain issues, including rare materials, are becoming important issues for sustainability and the further potential of advanced materials.

This section describes rare materials added to soft magnetic materials that constitute magnetic elements, their functionality, global market trends, and challenges.

2.5.2 Rare materials and their functionality

The addition of rare materials is extremely important to develop new soft magnetic materials with basic properties such as high saturation flux density, low coercivity, thermal stability, and corrosion resistance. **Table 5.2.5.1** summarizes typical rare material addition destinations, functionalities, and alloys after addition [(1)-(5)].

Boron (B) is an important element for amorphizing Fe- and Co-based alloys, and its addition reduces the coercive force and improves the soft magnetic properties by reducing the crystal magnetic anisotropy. It is mainly used in alloys such as Fe-B, Fe-B-Si and Fe-Co-B to refine their crystal grains and to obtain stable high-frequency magnetic properties over a wide frequency range. Niobium (Nb) is an essential element in nanocrystalline alloy materials such as Fe-Si-B-Nb-Cu. This element stabilizes the microstructure during heat treatment and can significantly improve the robustness and environmental resistance of the material itself. Cobalt (Co) is an element that can significantly increase the saturation magnetic flux density when combined with Fe. Cu is not a rare material, but like Nb, it is an important element in nanocrystallization and plays a role in controlling nanocrystallization during the heat treatment process of the alloy. Vanadium (V) is used as an additive element in Fe-Co alloys with high saturation density. The addition of this element improves phase stability and heat resistance. Zirconium (Zr) is an element mainly used in metallic glasses, a type of amorphous metal. Using this element improves oxidation resistance and soft magnetic properties. Molybdenum (Mo) is an element that, when added to Fe-Ni alloys, can reduce eddy current losses by lowering the coercive force and increasing electrical resistivity. In addition, research and development of winding materials (Cu) to reduce the use of wire materials is also gaining momentum due to the miniaturization of magnetic elements at higher frequencies [(6)].

By combining these elements with Fe-based alloys and Co-based alloys, it is possible to adjust the soft magnetic properties and high-frequency magnetic properties.

Table 5.2.5.1 Typical rare material addition destinations, functionalities and main alloys after addition

レアマテリアル	添加先	機能性	添加後に形成される主な合金
ホウ素（B）	アモルファス合金材料 ナノ結晶合金材料	結晶粒の微細化 （アモルファス相の促進）	Fe-B, Fe-Si-B,.Fe-Co-B, Fe-Ni-Si-B
ニオブ（Nb）	ナノ結晶合金材料	熱安定性および 耐食性の向上	Fe-Si-B-Nb-Cu(e,g, FINEMET®), Fe-Si-B-Nb
コバルト（Co）	高機能合金材料	飽和磁束密度の向上	Fe-Co, Fe-Co-V
銅（Cu）	ナノ結晶合金材料	結晶粒の核生成	Fe-Si-B-Nb-Cu, Fe-Si-B-P-Cu, Fe-Si-B-P-Cr-Cu
バナジウム（V）	アモルファス合金材料	軟磁気特性の向上・安定性, 損失の改善	Fe-Co-V
ジルコニウム（Zr）	アモルファス合金材料	結晶粒の形成, 軟磁気特性の改善, 耐食性（酸化抑制）	Zr-based bulk metallic glass
モリブデン（Mo）	ナノ結晶合金材料	低保磁力化, 電気抵抗率の上昇	Fe-Ni-Mo

レアマテリアル	添加先	機能性	添加後に形成される主な合金
ホウ素（B）	アモルファス合金材料 ナノ結晶合金材料	結晶粒の微細化 （アモルファス相の促進）	Fe-B, Fe-Si-B,.Fe-Co-B, Fe-Ni-Si-B
ニオブ（Nb）	ナノ結晶合金材料	熱安定性および 耐食性の向上	Fe-Si-B-Nb-Cu(e,g, FINEMET®), Fe-Si-B-Nb
コバルト（Co）	高機能合金材料	飽和磁束密度の向上	Fe-Co, Fe-Co-V
銅（Cu）	ナノ結晶合金材料	結晶粒の核生成	Fe-Si-B-Nb-Cu, Fe-Si-B-P-Cu, Fe-Si-B-P-Cr-Cu
バナジウム（V）	アモルファス合金材料	軟磁気特性の向上・安定性, 損失の改善	Fe-Co-V
ジルコニウム（Zr）	アモルファス合金材料	結晶粒の形成, 軟磁気特性の改善, 耐食性（酸化抑制）	Zr-based bulk metallic glass
モリブデン（Mo）	ナノ結晶合金材料	低保磁力化, 電気抵抗率の上昇	Fe-Ni-Mo

2.5.3 Global Rare Materials Market Trends

The market for rare materials used in soft magnetic materials is rapidly expanding as the adoption of these materials in electronic devices with high power conversion efficiency, renewable energy, and electric vehicles accelerates. Since each rare material has unique and superior properties, functional demand and strategic supply constraints have created individual markets as shown in **Figure 5.2.5.1**[(7)-(11)].

B oron (B) has a small market size of US$60 million, but is an important element in amorphous materials and is likely to grow to US$100 million by 2030 due to the increasing demand for lightweight, high-density magnetic elements in mobility applications such as EVs and aerospace. Niobium (Nb) is used in FINEMET® and other products, and its market size is expected to grow from US$2.9 billion in 2024 to US$4 billion in 2030 due to the growth of EVs and industrial automation. Cobalt (Co) is an essential element for improving saturation magnetic flux density in Fe-Co alloys, and its market size is expected to grow to US$19.7 billion in 2030, about 1.5 times larger than that in 2024 (US$12.2 billion). Copper (Cu) is used in a wide range of applications, not only in magnetic cores made of nanocrystalline alloy materials, but also in the entire electrical value chain. Therefore, it is the largest market, worth approximately US$240 billion in 2024, and is expected to grow to US$340 billion by 2030, in line with the progress of electrification on a global scale. For vanadium (V), the market size is US$3.4 billion in 2024 and is expected to grow to over US$4.5 billion in 2030, driven by demand for high-performance sensors and actuators. Zirconium (Zr) is an important element in acid-resistant bulk metallic glasses, with a market size of US$1.8 billion in 2024 and is projected to grow to US$2.7 billion by 2030. Molybdenum (Mo) contributes to the reduction of high-frequency losses (iron loss) in the Fe-Ni-Mo system, and its market size is expected to grow from US$4.7 billion in 2024 to US$6.1 billion in 2030.

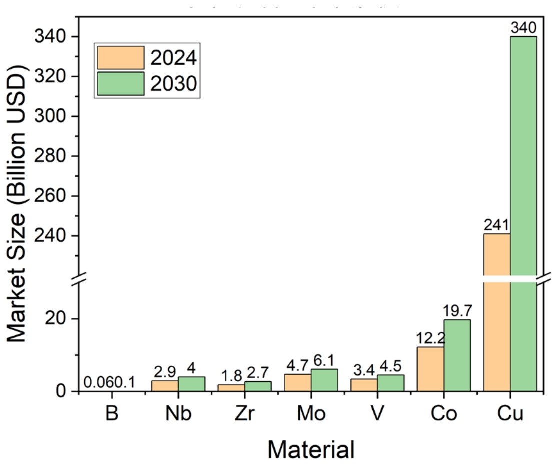

Figure 5.2.5.1 Rare Materials Market Size

As **shown in Figure 5.2.5.** 2, the Asia-Pacific region accounts for about 50% of the global total [(12)-(15)]. The region's dominance is attributed to the presence of large electronics and EV manufacturing facilities in China, Japan, and South Korea. North America and Europe follow the Asia-Pacific region, each accounting for about 20% of the market share. These regions are driven by their focus on cutting-edge R&D and their applications in aerospace, renewable energy, and industrial power systems. The rest of the world accounts for the remaining 10% and has the potential for future growth through region-specific electrification initiatives.

Market prospects in rare materials are being shaped by the convergence of technological advances and supply chain considerations. Growing awareness of geopolitical issues related to the sourcing of rare materials, intertwined with environmental and regulatory mandates, is highlighting the strategic importance of developing alternative supply chains and investing in recycling and sustainable sourcing technologies. It also suggests that the creation of soft magnetic materials with superior fundamental properties through the addition of rare materials can make an important difference in promoting compact and efficient power conversion systems globally.

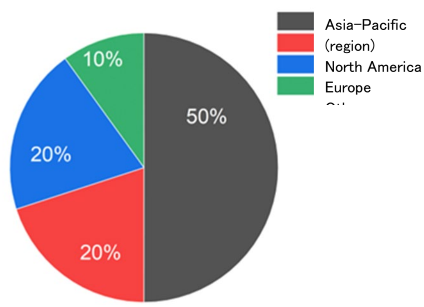

Figure 5.2.5.2 Rare Materials Consumption Rate by

This competitive environment is defined by ongoing R&D investments in rare materials, strategic sourcing, and capacity expansion to meet increasing global demand (**Table 5.2.5.2**).

Table 5.2.5.2 Major companies **and** businesses related to rare materials

企業 （国名）	事業
プロテリアル （日本）	EVや産業システムで利用されるFINEMET®ナノ結晶磁心を提供
VACUUMSCHHMELZE (VAC) （ドイツ）	優れた高周波応答を有するVITROPERM材料を提供
TDKエレクトロニクス （独国／日本）	フェライト磁心とパワエレ用先端材料を世界中に提供
Metgras Inc. （米国）	配電変圧器やEMI対策に利用されるアモルファス磁性合金に注力
Advanced Technology & Materials Co., Ltd. (AT & M) （中国）	ナノ結晶薄帯と磁心の製造を急速に拡大

2.5.4 Challenges and Future Directions

There are several challenges associated with the use of rare materials. The first is that some rare materials are expensive and difficult to obtain. This may limit scalability and increase the price of the final product. Second, adding rare materials to soft magnetic materials requires complex technologies such as rapid cooling and heat treatment in the material fabrication process, which may make mass production of the materials difficult. Third, environmental issues related to the mining and disposal of rare materials pose a challenge to regulation and sustainability.

On the other hand, as a future direction, we are in the process of developing recycling technologies and sustainable element procurement strategies in rare materials. In addition, in order to reduce dependence on scarce resources, research and development of composite soft magnetic materials combining nonmetals with good price-to-performance efficiency and small amounts of high-performance rare materials is underway. [Mai Phuong Nguyen, Satoshi Okamoto, Yasushi Endo].

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Section 3 In place of a summary

3.1 Coordination between circuit system area and passive device area

Keyword: High-speed semiconductor power devices, Passive components, Loss, Modeling, Data science, Integrated approach

As described above through this roadmap, research and development of high-speed semiconductor power devices such as GaN is progressing toward higher power density in power electronics devices, and passive components such as magnetic elements and capacitors are expected to become smaller and more efficient through high frequency switching. In practice, however, bottlenecks such as heat generation and limitations in miniaturization of passive components are becoming apparent, and an integrated approach to circuit system and material/element development is required.

In this section, based on what has been discussed in the previous chapters, we will review the issues of materials and device technologies for magnetic elements and capacitors, as well as the multifaceted issues surrounding passive components and materials, such as understanding loss generation mechanisms, advancement of measurement, observation, and modeling, and design methods that incorporate data science and AI/ML. The technical achievements and remaining issues will be reviewed. In this process, how material properties appear in device performance and how they are connected to circuit system requirements are positioned as viewpoints that should be shared by the materials side and the circuit side, and this roadmap is summarized in this section. The development of this roadmap into an international roadmap will also be briefly discussed.

3.2 Developmental Issues in Magnetic Devices

Keyword: High frequency transformer, Low Bs and low loss materials, Frequency-volume scaling, Magnetic powder core, Permeability tuning

3.2.1 Transformers and their materials

In order to realize high power density, it is traditionally required to create materials with both high saturation magnetic flux density (B_s) and low loss, and INNOPEL has created nanocrystalline alloy anisotropic thin ribbons with Co-Pd substituted FINEMET composition of 18 µm thickness and nanomet-based perpendicular magnetic anisotropic thin ribbon materials through advanced heat treatment [(1)]. The main issues for the future are the stable supply of rare elements such as Co and Nb, and the establishment of high workability and embrittlement suppression technology. For more information on materials for high-frequency transformers, please refer to 3.2.2 below.

Electromagnetic steel sheet is a strong Japanese technology, specializing in the production of world-class high-grade steel and creating high added value in both directional and non-directional applications. Recently, efforts have been made to reduce the environmental burden, for example, by hydrogen reduction steelmaking.

Ferrite materials are inexpensive, practical materials with a high degree of freedom in shape design, which were invented in Japan and have spread throughout the world, and will continue to be the mainstay materials for power electronics. In response to the spread of high-speed power devices, it is essential to elucidate the mechanism of loss generation in the high-frequency band and to further reduce the loss. In particular, it is important to elucidate the loss mechanism from the viewpoint of magnetic domain structure.

Since eddy current loss is generally inversely proportional to the square of the plate thickness, thin alloy strips with a thickness of 10 µm or less have the advantage of low eddy current loss in the high-frequency band. However, regardless of the material system, the saturation magnetic flux density as a magnetic core is low due to the low occupancy ratio, and the core molding handling is difficult and the degree of freedom of shape is low, so the power electronics applications are limited.

3.2.2 Expectations for Low *Bs* and Low Loss Materials for High Frequency Transformers

In high-frequency transformers operating above several tens of kHz, magnetic materials are often required to have low loss rather than high saturation flux density [(2)-(5)]. This is a higher requirement to keep the temperature rise within specifications and to balance volume and efficiency to suit the purpose. However, this requirement makes it difficult for material developers to predict the basic guidelines for material development and the size of the market, since it is difficult to foresee "at what level of high frequency band low magnetic flux density materials are useful. For this reason, it has been difficult to break away from the conventional development guideline of simultaneously pursuing high B_s, high µ, and low loss, and little research has been conducted on low B_s and low loss materials suitable for high-frequency transformers. Since demand for high-frequency transformers compatible with high-speed switching devices such as GaN is expected to expand in the future, it is desirable to further strengthen cooperation between the circuit side and the materials side to develop low B_s and low-loss materials.

In this case, it would be a good indicator if the relationship between the volume V of the magnetic element and the frequency f could be generalized, but it is not so easy to do so in actual equipment. This is because the allowable values of loss and temperature rise, cooling conditions and their allowable volumes, etc. are different for each device. First, if the operating magnetic flux density B_m is constant with respect to the frequency *f and* all losses are ignored, the magnetic core cross section A_c can be inversely proportional to the frequency according to Faraday's electromagnetic induction law ($A_c \propto f^{-1}$), and thus $V \propto A_c \propto f^{1}$ (frequency -1 power of the frequency). This relationship is ideal and easy to understand based on the fundamentals of electromagnetism, but it is far from being applicable to actual applications. Next, the relationship $V \propto A_p^{3/4}$ has been known since the 1970s between the area product $A_p = A_c$-A_w, which is the product of the magnetic core cross section A_c *and the* magnetic core window area A_W, *and the* magnetic core volume V.[6] [7] Combining this with the magnetic core cross section $A_c \propto f^{-1}$ described in the previous sentence, $V \propto f^{-3/4}$ (frequency to the -0.75 power) is obtained. It has been pointed out that this relationship is only plausible up to a few kHz [8]. Finally, a 2007 statistical report on a large number of actual machines stated that "power density has roughly doubled in the decade since 1970" and "switching frequency has increased tenfold in that time" [9]. A simple combination of these two factors yields $V \propto f^{-0.3}$ (-0.3 to the power of frequency). All of the above three examples show that magnetic elements can be made smaller by increasing the frequency, but as can be seen from the fact that the exponents obtained swing widely from -0.3 to -1.0, the relationship between frequency and volume strongly depends on the application and preconditions. This is the reason why collaboration between the circuit side and the material side is strongly desired in the development of low B_s and low loss materials.

3.2.3 Inductors and their materials

In INNOPEL, pressed magnetic cores using plate-like and flat powders of iron-based nanocrystalline materials and Nanomet magnetic cores with high density filling by hot forming, etc. have been developed. In the development of these magnetic powders, it is necessary to clarify the relationship between the variation in particle size, magnetic properties of the material, and device properties, and to identify and solve problems that need to be solved before mass production.

In general, filling the gaps between magnetic particles in a pressed magnetic core with submicron-sized magnetic particles promotes high saturation magnetic flux density and low loss. The challenges are the combination of materials, industrial production methods for submicron-sized magnetic particles, and the construction of uniform dispersion methods. Please refer to 3.2.4 below for information on permeability tuning in a magnetic powder core.

On the other hand, a prototype of bulk α" iron nitride material was fabricated at INNOPEL, and iron loss measurement was possible for the first time as a magnetic core. It is necessary to continue to boldly search for breakthroughs with zero crystalline magnetic anisotropy and to explore the possibility of magnetic materials for future power electronics as the ultimate high saturation magnetization magnetic materials. [Masahiro Yamaguchi]

3.2.4 Permeability Tuning in Magnetic Powder Core

Powdered magnetic cores are widely used in inductors for power electronics applications because of their low loss characteristics, isotropic electromagnetic properties, and freedom in forming complex three-dimensional shapes. It is very useful if the magnetic permeability can be controlled (tuned) to a desired value, the accuracy of which directly affects the performance and reliability of the final product. The guideline for permeability tuning technology is to control the volume filling ratio (density) of magnetic particles , and Ollendorff's formula, which assumes that the magnetic particles and the insulating layer are homogeneous, has been known for many years [10].

$$\overline{\mu_r} = 1 + \frac{\eta(\mu_r - 1)}{1 + N(1-\eta)(\mu_r - 1)} \qquad (5.3.2.1)$$

where $\overline{\mu_r}$ is the average specific permeability of the magnetic powder core, η is the volume filling factor of the magnetic particles, μ_r is the specific permeability of the magnetic particles, and N *is* the antimagnetic field coefficient.

Recently, it has been found that when a magnetic powder core is compressed under high forming pressure, the insulation layer between the particles breaks locally and the particles contact each other magnetically (non-contact magnetostatic coupling) or electrically, of which magnetic contact decreases the antimagnetic field coefficient *N*and significantly increases the average specific magnetic permeability of the magnetic powder core [11]. This is **shown in Figure 5.3.2.1**. In the figure, the volume filling ratio of a typical magnetic powder core is in the range of 0.8 to 0.9. It is important to note that in this range, a slight change in the volume filling ratio significantly changes the magnetic permeability. Since the saturation magnetic flux density of a pressed core is almost proportional to the volume filling ratio, it is possible to control the magnetic permeability while keeping the saturation magnetic flux density almost constant.

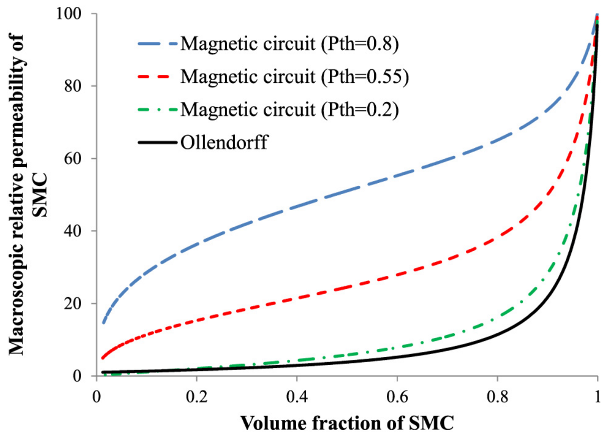
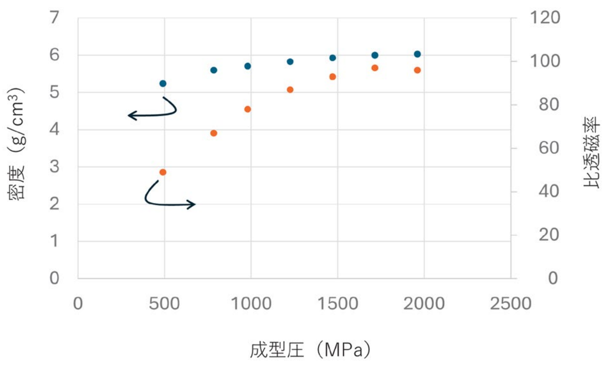


Figure 5.3.2.1 Relationship between volume filling ratio of magnetic particles and average specific permeability in a piezoelectric core [11]

INNOPEL has achieved a permeability change of 34 % for an 8 % density change in Fe-based nanocrystalline magnetic powder cores. As shown in Figure 5.3.2.2, we have also demonstrated that the permeability can be tuned in the range of 60.6 to 94.5 for Fe-Si-Al (sendust) magnetic powder cores. In this case, the change in permeability ranges up to 36 % for a 6 % change in density. Since this technology is based on reducing the molding pressure in the manufacturing process of commercially available high-density magnetic powder cores, it does not damage magnetic particles or grain boundaries, maintains good insulation between magnetic particles, and does not increase eddy current losses, making it useful as an inductor for high frequency bands.



In the future, it may be possible to tune a wider range of permeability by increasing permeability through magnetic contact. However, if not only magnetic contact but also electrical contact occurs, excessive eddy current loss occurs between particles, especially in the high-frequency range, and the low loss property, which is the greatest advantage of the magnetic powder core, may be impaired. Therefore, it is important to design materials and processes that simultaneously satisfy the contradictory conditions of "achieving the targeted magnetic permeability and suppressing eddy current losses to an acceptable level.

[Ryota Kunieda, Mai Phuong Nguyen, Eikichi Yoshida]

3.2.5 Mechanism of loss generation in magnetic materials

Research has progressed toward a more detailed understanding of loss factors, and INNOPEL, based on the findings of the Italian National Metrology Institute (INRiM), has shown that for many practical power electronics materials, losses can be separated into magnetization rotation (reversible) and magnetization reversal components of magnetization wall shift (irreversible), and in the power electronics band In the power electronics band, the contribution of the magnetic wall shift component was found to be large up to high frequencies above 100 kHz.

We would like to clarify the magnetostriction-induced loss as a loss related to the magnetic wall movement and develop a new low-loss magnetic element for power electronics based on this knowledge.

3.2.6 Measurement, Observation and Modeling

In iron loss measurement, there was a dilemma that the lower the material loss, the more difficult the measurement became, but now, for low power, sufficient accuracy can be obtained for power electronics development. In the future, it will be necessary to develop measurement methods for high power measurements of 10 kW or more, higher frequencies, and actual operations such as PWM. It will also be necessary to construct a method to efficiently measure large amounts of iron loss data to create a database for use in constructing loss maps and acquiring teacher data for machine learning.

In the magnetic domain observation method, a time-resolved vector (three-dimensional) magnetic domain observation system has been developed, with a wide bandwidth of MHz or more and much improved sensitivity and spatial resolution. We have also succeeded in observing magnetic domains in ferrite materials, an unprecedented achievement. In the future, by clarifying changes in magnetic domain behavior with respect to frequency and magnetic flux density, and through synergistic effects with the knowledge of loss generation mechanisms described in the previous section, it is expected that the generation mechanisms of abnormal eddy current loss and residual loss, which have remained unresolved for many years, will be clarified, and new development guidelines for low-loss materials will be established.

In modeling, progress has been made from physical processes to circuit models. In the future, it is expected to link them together to build an integrated platform from material and element development to power electronics circuits and their system implementation methods, as well as to contribute to an inverse problem approach to present passive element characteristics and material requirements desired by power electronics circuit systems as indicators (see Chapter 4, 2.4). (See Chapter 4, 2.4).

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3.3 Developmental Issues in Capacitors

Keyword: High voltage resistance, High heat resistance, Conductive polymer, Thin film, Paraelectric, DC bias characteristics, Dielectric constant

3.3.1 electrolytic capacitor

Aluminum electrolytic capacitors are widely used in PWM inverters because of their large capacitance and low cost. Although they used to be considered low-life and high loss capacitors, recent technological developments have eliminated this problem, and products with 10,000 hours at 105 ℃ and 135 ℃ capacitors for automotive use have been commercialized. In addition, hybridization with functional polymers has led to the commercialization of capacitors up to 80 V. The temperature characteristics of aluminum electrolytic capacitors due to the electrolyte have been overcome, and they are used in DC link (smoothing) circuits of DC-DC power supplies, for example.

INNOPEL has been working on the development of conductive polymer electrolytic capacitors with low ESR and excellent high-frequency characteristics, as well as with high withstand voltage and high heat resistance. The performance verification of 450 V 150 ℃ multilayer capacitors is in progress. In the future, it will be necessary to promote even higher withstand voltage (1000 V) to meet the demand for EVs and other applications.

3.3.2 film capacitor

They are used in DC link circuits for connecting the DC power supply of main inverters for vehicles, snubber circuits, and filter and resonance circuits from several 10 Hz to several kHz. The features include excellent impedance characteristics in the frequency band of several 10 kHz, self-healing, no flammable electrolyte, open failure mode, high safety, and long life. On the other hand, it is sometimes pointed out that the temperature characteristics of film capacitors are low, but recent technological developments have resulted in the commercialization of heat-resistant capacitors with a temperature resistance of 125 °C. Polypropylene has been the main dielectric material used in film capacitors for DC applications, but the thin-film capacitors are approaching their limits in terms of 10 to 20 years from now. In the future, it will be necessary to reduce the number of dielectric breakdown points by making the space charge distribution uniform within the element, and to develop new dielectric materials with high heat resistance and high dielectric constant.

3.3.3 Ceramic Capacitors

They are used in resonant circuits from several kHz to several 10 MHz, flying capacitors, coupling, decoupling, and other applications. The features of these capacitors are small size, high reliability (long life), and low ESR.

INNOPEL has been focusing on paraelectric materials that have a low dielectric constant but are stable at high temperatures and have good DC bias characteristics, and has discovered rutile-type TiO_2 and titanite-based oxides with dissimilar element substitutions.

As the number of users increases due to thinner and higher performance information terminals and to higher performance electronic devices and automobiles, etc., further miniaturization and larger capacitance are required.

3.4 Utilization of Data Science

Keywords: power-element AI, surrogate model, nonlinear characteristics, integrated optimization, large-scale language model, inverse problem

With regard to the utilization of data science, which has been rapidly developing recently, a guideline to develop a set of AI (power electronics AI) and physical implementation (elements and circuits) according to the purpose is expected to be effective in the future. In the conventional circuit design process, a wide range of processes from requirement definition, topology selection, component value determination, thermal design, and reliability evaluation required trial-and-error based on the experience of skilled designers, but the introduction of AI/ML has led to automation and shortened design cycles. Surrogate models are particularly useful for high-precision circuit simulations and physical models with high computational costs [(1)], for example, to estimate circuit output performance and predict temperature fluctuations and annual degradation of semiconductor device junctions at high speed. Since the characteristics of magnetic components have nonlinear dependence on current-voltage and frequency, which are difficult to be adequately reproduced by conventional physical models, AI/ML is expected to play a central role in precisely predicting nonlinear characteristics of passive components, optimizing integration between circuit design and material development, and solving inverse problems.

AI/ML has great potential throughout the lifecycle of power electronics systems, including real-time control, fault prediction, topology selection, and multi-objective optimization (simultaneous optimization of efficiency, cost, and environmental impact), and large-scale language models (LLMs) will be used even more in the future.

Reference

(1) Kan Akatsu: "Transformers for SSTs", Chapter 1, 3.3 (2026) of this roadmap.

3.5 Development into an IEEE Collaborative International Technology Roadmap

Keyword: Magnetic device roadmap for power electronics, IEEE Technology Roadmaps Committee

As mentioned repeatedly in this roadmap, a new framework is being formed in Japan, in which power electronic devices, circuit systems, passive components, and materials are integrated through the collaboration of power devices, circuit systems, and passive components/materials. By promoting research and development while deepening mutual understanding between the material and circuit sides, new value is being created in many areas, including new materials, observation methods, modeling, and methods for utilizing materials, and the results are being shared not only domestically but also internationally.

As a part of this effort, INNOPEL's systematic approach to "redefine the relationship between requirements and material properties through collaboration between materials and circuits" has attracted much interest from both the IEEE Magnetics Society (MagSoc) and the IEEE Power Electronics Society (PELS), and both societies recognize the significance of developing this into an international roadmap. Both societies recognize the significance of developing this into an international roadmap. On the other hand, the INNOPEL Passive Device Technology Roadmap is structured mainly from an academic perspective, leaving out of scope trends specific to each region of the world, industry links, and standardization trends, etc. MagSoc and PELS have expanded the scope in light of these circumstances, and are working to develop a roadmap that meets the IEEE's definition of an MagSoc and PELS are discussing to expand the scope based on these situations and to develop a roadmap of magnetic elements for power electronics that meets the International Technology Roadmap defined by the IEEE. As part of this systematization, PELS intends to clarify the specifications of magnetic passive components required by major applications (data centers, EVs, renewable energy systems, etc.) from the circuit side and to reexamine the validity of requirements that have been too generalized in the past (simultaneous pursuit of high Bs, high μ, and low loss).

The development from the INNOPEL roadmap to the IEEE roadmap was proposed in April 2025, and in August/September of the same year, the Administrative Committee (AdCom) meetings of MagSoc and PELS, respectively, approved the direction to develop the Intersociety project (tentative name) Magnetic Passive Components for Power Electronics as an Intersociety project was approved at the Administrative Committee (AdCom) meetings of MagSoc and PELS in August and September of the same year. Both Societies and INNOPEL have nominated the members of the leadership team, and it was confirmed that the direction of the roadmap will be finalized through further discussions. After the approval, the activities of both societies are expected to officially start and the roadmap will be formulated in earnest. The international impact of the INNOPEL roadmap is expected to extend beyond magnetic devices to a wide range of areas, including capacitors and their materials, as well as research and development of power devices, and to provide an opportunity to open new prospects for power electronics as a whole.

[Masahiro Yamaguchi]

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	(E-mail address: kankyou@mext.go.jp Telephone: 03-6734-4159)