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High-Frequency Resistivity of Soft Magnetic Granular Films

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Co-Zr-O granular films were prepared by reactive sputtering. The films show strong uniaxial in-plane anisotropy as well as good soft magnetic properties and high dc resistivity. In order to confirm their electrical characteristics at high frequency, the frequency and current density dependences of resistivity were investigated. Resistivity was found to be constant over the range measured (up to 18 MHz and 100 MA/m²). Furthermore, the films exhibit virtually no hysteresis along the hard-axis direction and have very little anisotropy dispersion. The frequency dependence of the initial permeability was measured and used to predict the power loss expected when granular films are used as high-frequency core materials for film inductors. The power loss is predicted to be lower than that of commercial NiZn ferrite for high-frequency applications.

***Index Terms*—Granular film, high-frequency resistivity, initial permeability, power loss, soft magnetic film.**

I. INTRODUCTION

SOFT magnetic granular films are considered ideal core materials for thin-film inductors applied in high-frequency integrated dc-to-dc converters and similar applications [1], [2]. Their high saturation magnetization M_s , high in-plane anisotropy field H_k , and high resistivity ρ are beneficial to obtain high power density and low power loss in thin-film inductor applications. The resistivity of granular films is generally evaluated by small-signal dc measurements. In soft magnetic granular films, magnetic particles are embedded in oxide insulating matrix phases, which results in high dc resistivity [3]. When the materials are applied at very high frequency, the possible capacitance between magnetic particles in granular films may decrease the impedance, resulting in increased eddy currents. Furthermore, the induced electric field increases with increasing frequency of the time-varying magnetic field. A high induced electric field may, in addition to linearly increasing eddy-current density, give rise to nonlinear effects such as tunneling. Although many studies have been done on high-resistivity granular films, most of them are concerned with the films' magnetic properties and microstructure [4]–[6] rather than their high-frequency electric properties [7]. For this reason, it is necessary to confirm the electric characteristics of granular films at high current density as well as at high frequency.

II. EXPERIMENTS

Soft magnetic Co-Zr-O granular films [8], [9] were deposited by dc magnetron sputtering on glass slides and Si wafers in an Ar + O₂ atmosphere using a CoZr alloy target (Co : Zr = 85 : 15 atomic ratio) and a water-cooled substrate table. The base pressure of the chamber was better than 3×10^{-7} torr. Sputter power was set at 100 W, sputter pressure was 1.2 mtorr, and oxygen introduction was varied from 6% to 10%. A Halbach magnet array providing a 40-mT in-plane field was used to induce in-plane anisotropy in the films. Magnetic properties

and small-signal dc electrical resistivity were measured with a vibrating sample magnetometer (VSM) and a conventional four-point probe. The microstructure was characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). Detailed results of these measurements are reported in [9]. The frequency dependence of the initial permeability was evaluated by a high-frequency permeameter (Ryowa PMF-3000). A waveform generator and an ac amplifier (Hafler trans nova P4000) were used to apply high-frequency voltage to a sample and generate high ac current density. The ac current and voltage were measured by an ac current probe (Tektronix P6021) and a differential voltage probe (Agilent 1141A), respectively. Waveforms of the ac current and voltage were monitored on an oscilloscope. The samples were connected using separate contacts for current and voltage, as in the four-point probe method, but with a rectangular geometry (30 mm \times 5 mm) to provide uniform current density.

III. RESULTS AND DISCUSSION

The prepared Co-Zr-O films of thickness from 0.5 to 10 μm show strong in-plane uniaxial magnetic anisotropy [9]. Fig. 1 gives an example of their B - H loops along the easy- and hard-axis directions. From this figure, it is apparent that uniaxial magnetic anisotropy nearly has no dispersion and B - H loops show virtually no hysteresis. These films exhibit a saturation flux density B_s of 1.0–1.3 T, H_k of 0.16–1.20 kA/m, and ρ of 180–640 $\mu\Omega\text{ cm}$. Their hard-axis coercivity H_c is in the range of 5–400 A/m. The properties are very good for use in film inductors.

Fig. 2 gives the frequency dependence of resistivity for a Co-Zr-O granular film. By varying the frequency of ac current, we found that in the measured frequency range (from 4 kHz to 18 MHz), the resistivity of the film stays constant at 590 $\mu\Omega\text{ cm}$, which is the same as its dc value measured by the conventional four-point probe method. By monitoring the current and voltage waveforms, we also found that the current and voltage were nearly always in phase over the whole measured frequency range, indicating that the impedance of the film is purely resistive. When the rms value of the ac current density was increased from 1.9 to 61.0 MA/m², similar results were

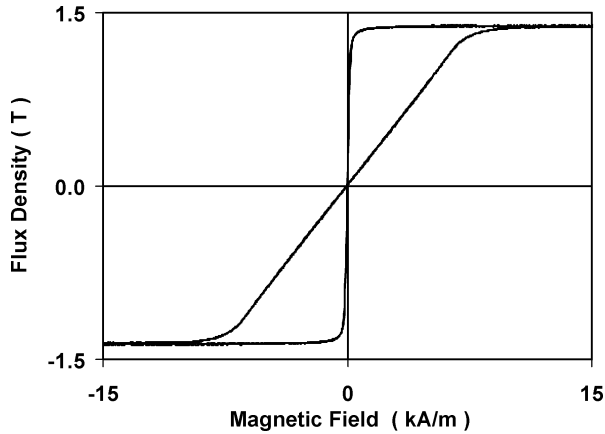


Fig. 1. B - H loops along the easy and hard axes for a Co-Zr-O granular film.

observed. This implies that resistivity is also independent of the current density. In order to confirm this, we made detailed measurements of the current density dependence of resistivity at 100 kHz and 10 MHz. Fig. 3 shows the results of these measurements for the Co-Zr-O granular film. With increasing ac current density up to 100 MA/m², the waveforms of ac current and ac voltage are always in phase and the resistivity remains unchanged at its dc value. When the current density was increased to about 200 MA/m², the film burned off of the substrate. We also measured four other films with dc resistivities of 182, 280, 332, and 633 $\mu\Omega$ cm, and found that these films show similar characteristics to the film described above. If a soft magnetic film is applied as the core material for an inductor, it is easy to calculate the peak value of the eddy-current density J_{eddy} in the film, on the condition that the penetration depth is higher than half of the film thickness d , by using Faraday's law and Ohm's law. The result is

$$J_{\text{eddy}}(y) = \frac{2\pi f y B_m}{\rho}. \quad (1)$$

Here, ρ is the resistivity of the film, y is the distance from the center plane of the film, and B_m is the amplitude of a sinusoidally varying flux density at frequency f . The maximum eddy-current density occurs at the surface of the film ($y = d/2$). To find a numerical value for current density, we consider an example application, the V-groove inductor for microprocessor power delivery discussed in [10]. In this application, soft magnetic Co-Zr-O granular films with 10- μm thickness are applied at 10 MHz. Although the ac flux density amplitude B_m in this application is lower than the saturation flux density B_s , transformers or inductors for other applications could have an ac flux density amplitude of up to B_s , so we consider the current density with $B_m = B_s$. With a dc resistivity of 590 $\mu\Omega$ cm and B_s equal to 1.2 T, the maximum rms value of eddy current density is calculated using (1) as 44.4 MA/m². This is within the range of current densities tested, in which the film exhibited linear behavior. Thus, standard eddy-current loss calculations that may be derived from (1) apply.

In order to predict the power loss of granular films at high frequency, we measured their initial permeability with a PMF-3000 high-frequency permeameter. Fig. 4 shows an example of the frequency dependence of initial permeability

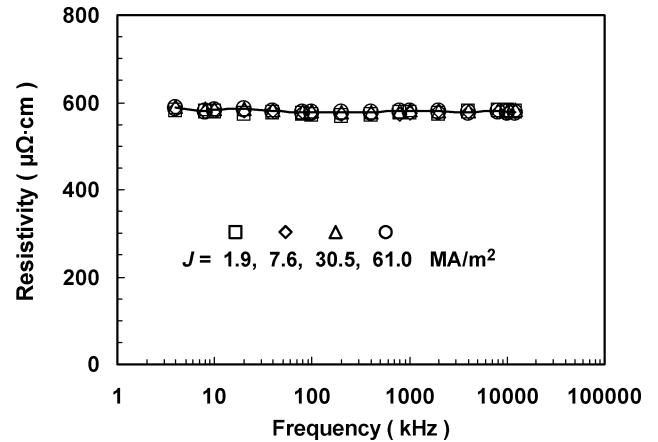


Fig. 2. Frequency dependence of resistivity for the granular Co-Zr-O films measured at four rms current densities J .

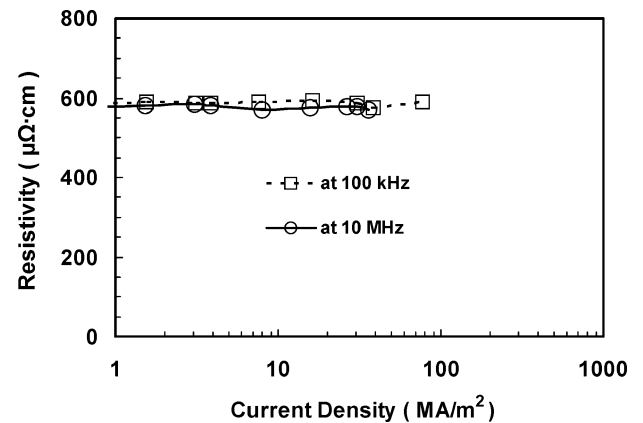


Fig. 3. Current density dependence of resistivity for the granular Co-Zr-O films. In this figure, current density is the rms value.

for a Co-Zr-O film. The points marked with \circ and Δ are measured results of real and imaginary parts of the complex initial permeability. The solid lines are the calculated results with the Landau-Lifshitz equation, including the eddy-current effect [11]. This figure shows excellent agreement between measured and calculated values. It can also be seen that the film has very low imaginary permeability, showing the contribution from high resistivity and large anisotropy. The quality factor Q is as high as 35 when the frequency of applied magnetic field is 100 MHz.

As mentioned before, the measured B - H loops show that there is nearly no anisotropy dispersion. Therefore, it is reasonable to assume that the amplitude permeability of the granular Co-Zr-O film is nearly equal to its initial permeability when it is operated below saturation. The measured B - H loops also exhibit virtually no hysteresis as a result of the strong in-plane uniaxial anisotropy. Thus, power loss of the granular films can be expected to result primarily from linear phenomena such as eddy currents, which are accurately reflected in small-signal complex permeability measurements. The specific power loss P_v can be found from the complex permeability by considering the area of the B - H loop [12], resulting in

$$P_v = \frac{\pi f \mu_r'' B_m^2}{\mu_0(\mu_r'^2 + \mu_r''^2)}. \quad (2)$$

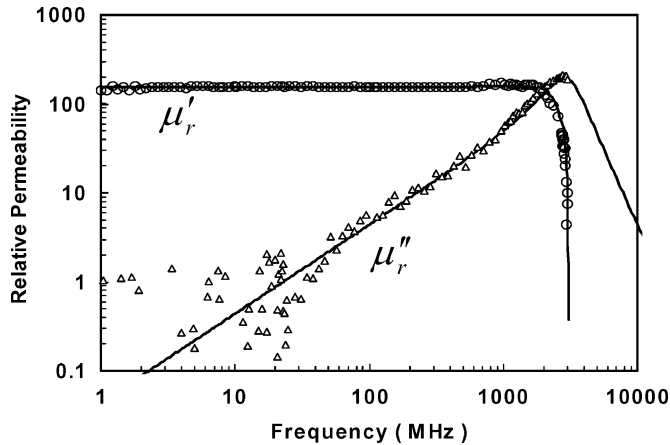


Fig. 4. Frequency dependence of initial permeability for the granular Co-Zr-O films. \circ and Δ are measured data of real and imaginary parts of the complex initial permeability. The solid lines are calculation results.

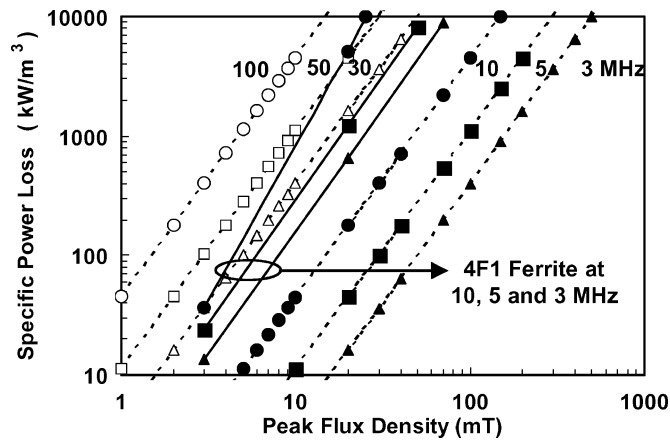


Fig. 5. Peak flux density dependence of specific power loss for granular Co-Zr-O films (dashed lines) and 4F1 NiZn power ferrite (solid lines). Marks represent different frequencies: \blacktriangle , 3; \blacksquare , 5; \bullet , 10; \triangle , 30; \square , 50; and \circ , 100 MHz.

Here, μ'_r and μ''_r are real and imaginary parts of the relative complex initial permeability, respectively. Fig. 5 shows the calculated flux density dependence of the specific power loss for the granular Co-Zr-O film. Here, using frequency as a parameter, we calculated the specific power losses at 3, 5, 10, 30, 50, and 100 MHz using (2), and plotted the results in the figure with dashed lines. For comparison, we also plotted the manufacturer's measured data for a commercial NiZn soft power ferrite (Ferroxcube 4F1) at 100°C. Loss in 4F1 is minimized near 100°C, whereas our results indirectly indicate that the loss in granular films does not vary strongly with temperature. Thus, making the comparison at this temperature favors the 4F1 material. These calculations indicate that, compared to 4F1 soft power ferrite, Co-Zr-O granular films will have a much lower power loss at the same frequency and will be capable of power application at higher frequency. Although cost is likely to be higher, these Co-Zr-O granular films are definitely good options as cores for inductors, especially for integrated film inductors.

IV. SUMMARY

Evaluation of the frequency and current-density dependences of the resistivity, and frequency dependence of the initial permeability of soft magnetic Co-Zr-O granular films indicated that, at least up to 18 MHz, the ac resistivity remains the same as its dc value. Even at a current density of 100 MA/m² at 10 MHz, the ac resistivity seems unchanged. Therefore, the films' electrical behavior can be treated as linear. It was also found that the measured value of high-frequency complex permeability for granular films is in good agreement with the value calculated by the Landau-Lifshitz equation. The amplitude permeabilities of the granular Co-Zr-O films can be expected to be nearly equal to their initial permeabilities. On this basis, the power loss was predicted to be much lower than that of commercial NiZn power ferrite.

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