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ScienceDirect
Journal of Magnetism and Magnetic Materials 312 (2007) 245–251
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Non-linear tunneling charge transport in soft ferrites

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Received 4 July 2006; received in revised form 30 September 2006
Available online 10 November 2006

Abstract

To better understand the high-frequency magnetic loss mechanisms in soft ferrites, we measured the conductivity of the soft ferrites for large values of the electric field. We found that the conductivity is highly non-linear. We show that this non-linearity is consistent with charge tunneling through thin insulating films separating adjacent ferrite grains. This non-linear conductivity can be used to obtain observed flux density dependence of the high-frequency magnetic loss. This flux dependence of the high-frequency loss previously remained anomalous.

Keywords: Tunneling; Non-linear; Conductivity; High frequency magnetic loss; Charge transport

1. Introduction

Soft ferrites are commonly used in the cores of high-frequency magnetic components such as transformers and inductors for applications in power electronics such as high-frequency DC–DC converters [1]. During the last two decades the operating frequencies of these magnetic components and power electronic circuits had been pushed up from 10's of kHz to ~1.0 MHz to reduce the size of the magnetic components. However, the size reduction was not as substantial as was originally thought and the magnetic components remain the largest part of the power electronic circuits [2]. This is mostly due to the high losses in soft ferrites at high frequencies, which forces one to reduce the operating flux density.

Considerable efforts have been devoted to improving the loss characteristics of soft ferrites using conventional techniques like reducing the size of the grain, increasing the amount of the insulators such as SiO_2 and CaO at the grain boundaries, and making the sizes of the grains more uniform [3,4]. However, the losses remain high mainly due to the lack of proper understanding of the high-frequency loss mechanisms in the ferrites when they are driven at high flux levels and high frequencies.

It is commonly believed that the dominant magnetic loss mechanism at high frequencies is the classical eddy current-loss component [1,4]. This is mostly inferred from the approximately quadratic frequency dependence of the experimental loss. However, it has been found that there is poor correlation between the measured conductivity (low field) and the observed losses. Further, in contrast to the square dependence of the theoretical loss on the flux density, the observed exponent of the flux density is three or higher. This strongly indicates that some other phenomenon is responsible for the observed loss characteristics [4,5].

As we demonstrate in the next section, when the ferrite is driven at high flux level at high frequencies, large electric fields are induced in the ferrite body. Thus, it may not be appropriate to use the low field conductivity in the calculation of the high-frequency loss. With this as a clue, we measured the electrical conductivity of the ferrites for large electric fields and found that the electrical conductivity is not constant but increases sharply as the electric field gets very large. We also show that this non-linear charge transport is consistent with inter-granular charge tunneling between adjacent grains through the insulating films separating them. Previously, it has been shown that tunneling plays an important part in the charge transport of a number of many other granular materials [6–13].

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0304-8853/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.jmmm.2006.10.162

The remaining paper is organized as follows. In Section 2, we first demonstrate that large electric fields are generated inside the field when the ferrite is driven at high flux levels at high frequencies as a motivation for measuring the electrical conductivity for large electric fields. In Section 3, we describe our measurements, and the tunneling theory is described in Section 4. In Section 5, we demonstrate how non-linear conductivity can be used to obtain a more satisfactory theory of high-frequency magnetic loss in ferrites, which provides further support for ideas presented in this paper. Section 6 includes a few concluding remarks including the mention of applications of ideas to other granular magnetic materials such as various grades of steel and iron. In this last section, we also mention a new ferrite structure that can reduce electric field generated at the grain boundaries leading to reduced charge tunneling and reduced high-frequency magnetic loss.

2. Electric fields

Our measurement of non-linear conductivity in ferrites is motivated by the estimates of electric field that typically exists inside a ferrite while operating at high frequencies (200 kHz–1.0 MHz), which indicate that use of low field conductivity to estimate eddy current loss in ferrites is not appropriate at such high frequencies. We present these estimates for the core size, which is typical for power electronics applications. We assume a cylindrical core piece with circular cross-sectional area of radius of $r = 1\,\text{cm}$ as shown in Fig. 1. For a frequency f, the induced emf ε around a circular path of radius $\sim r$ for a flux density B is

$$\varepsilon = 2\pi f(\pi r^2)B = 2\pi^2 r^2 (fB). \qquad (1)$$

The circular path is also shown in Fig. 1 as a dotted line. Please note the linear dependence of this induced emf on the frequency and flux density. In particular for large frequencies and flux densities, this emf could be very large. To estimate the average electric field E, we divide this induced emf by the length of the circular path to obtain

$$E \equiv \frac{\varepsilon}{2\pi r} = \pi r(fB). \qquad (2)$$

Once again we note that this electric field increases linearly with the frequency and the flux density. Thus for high frequencies and flux densities, the electric field could be very large. We used Eq. (2) to estimate the electric field for a set of values of flux densities and frequencies and the results are shown in Table 1.

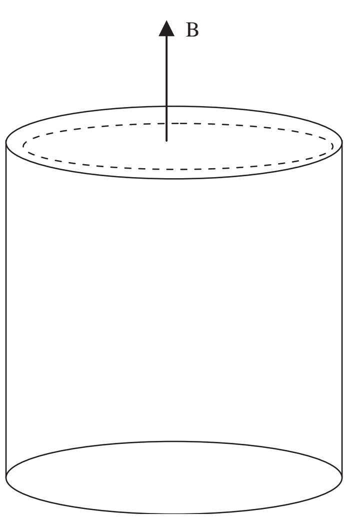

Fig. 1. A cylindrical ferrite piece with a time varying flux Density B. Dashed line represent the circular path used for calculating induced emf and electric field.

Table 1
Electric field induced in the core

Frequency (MHz)	Flux density gauss (mT)	Electric field (V/m)
1.0	1000 (1 0 0)	3140
1.0	500 (50)	1570
0.5	1000 (1 0 0)	1570
0.5	500 (50)	785

3. Measurements

Two $0.5 \times 0.5 \times 0.5\,\text{cm}$ samples of high-frequency-power MnZn ferrites were prepared. Electrical contacts were attached at the two opposite faces using conducting paste. The measurement setup is shown in Fig. 2. In this setup a signal generator is used to produce a sinusoidal signal in the frequency range of 100 kHz–10 MHz. The output of the signal generator is fed into an RF amplifier, which can amplify the signal up to a desired output peak voltage. The output of the amplifier is connected to a circuit in which a 1.0-Ω power resistor is connected in series with the sample. To measure the voltage across the sample, one channel of an oscilloscope was connected directly across the sample. The current was measured by a second channel, which was connected across the 1.0-Ω power resistor. These measurements match the DC conductivity measurement, thereby giving us confidence in our AC measurements.

Temperature was monitored throughout the measurements and forced air was used for cooling at higher applied voltages. Also for higher applied voltages, all the measurements were performed during the first few minutes of the application of the power to the sample to avoid any temperature effects. The temperature was observed to remain around 10 K of the room temperature. The current as a function of voltage was measured at 300 kHz, 500 kHz, and 1 MHz. The experimental results at 300 kHz are shown in Fig. 3 for one sample (the results for the other sample are similar). A close examination of the results shows that for small voltages the current varies linearly with voltage while for larger voltages the current rises exponentially. To clarify, we calculated the conductivity from this data and, in Fig. 4, we show the conductivity as a function of the electric field. Please note that the larger electric fields