A high-performance permeance meter and its application to measuring the complex permeability of thin Fe-Si-Al-N films for perpendicular magnetic recording heads

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A high-performance permeance meter and its application to measuring the complex permeability of thin Fe-Si-Al-N films for perpendicular magnetic recording heads

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A high-performance permeance meter has been developed to measure the permeability of thin films for perpendicular magnetic recording heads. The instrument is able to determine small permeance (about 20 μm) with a good signal-to-noise ratio in the frequency range of 0.5–120 MHz and, moreover, to reduce the conventional error in the high-frequency region. The complex permeability of an Fe-Si-Al-N film 200 nm thick for perpendicular magnetic recording heads was measured, and the real part of the permeability was about 3500 with a $-$1-dB frequency of about 80 MHz.

I. INTRODUCTION

Thin films of high permeability and a low loss in the high-frequency region are needed for high-performance perpendicular magnetic recording heads, and so it is necessary to measure accurately the permeability of thin films in the high-frequency region.

Some methods of measuring the high-frequency initial permeability of thin anisotropic films have been proposed.[1–3] One uses two sense coils, one to measure the flux in a sample (B coil) and the other to measure the magnetic field (H coil).[1] Others use only a B coil. The latter method, however, needs either knowledge of the magnetic field obtained by another method, for example, the finite-element method,[2] or a reference sample of known permeance.[3]

The most important error in the high-frequency region when using two coils results from differences between the transfer functions from the coils to a sense amplifier.

A resister has been used to equalize the time constant of the two coils.[1] However, this technique decreases the voltage at the sense amplifier and therefore degrades the signal-to-noise (S/N) ratio. Furthermore, since the inductance of the coils changes with the permeance of the sample in the B coil, it is difficult to equalize them adaptively.

We overcame these difficulties by measuring the transfer function directly. The new instrument has a frequency range of 0.5–120 MHz and a good S/N ratio. It can determine small permeance (about 20 μm) with a good S/N ratio.

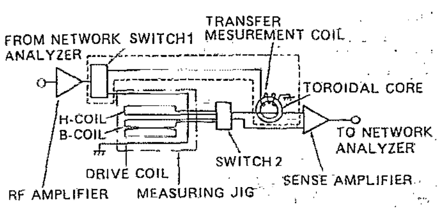

FIG. 1. Block diagram of the permeance measurement system without network analyzer.

II. APPARATUS

The instrument is composed of a network analyzer and a permeance measuring jig. Figure 1 is a block diagram of the measuring system without the network analyzer. The circuit enclosed by the dotted lines, which includes select switch 1 and a coil wound on a toroidal core (transfer measurement coil), is used to determine the transfer function from the sense coils to the sense amplifier. One of the lines from select switch 2 to the sense amplifier passes through the toroidal core. The transfer function is measured by turning the select switch 1 so that the current is applied to the transfer measurement coil.

Figure 2 shows the arrangement of the measuring jig. The dimensions of the H coil and the half B coil are 1.3 mm high and 16 mm wide, and the sample substrate is 10 mm wide, 10 mm long, and 1 mm thick.

III. THEORY OF MEASUREMENT

The principle of the measurement, except for the measurement of the transfer functions, is the same as in Ref. 1. The permeability μ of the sample is given by following equation:

$$\mu=(S_h/S_s)[(V_b/V_h)/(G_b/G_h) - (V_{b0}/V_{h0})/(G_{b0}/G_{h0})], \quad (1)$$

where S_h = area of the H coil, S_s = area of a sample cross section, V_b = voltage induced in the B coil with a sample, V_h = voltage induced in the H coil with a sample, G_b = transfer function from the B coil to the sense ampli-

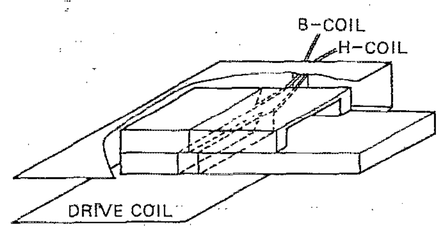

FIG. 2. Permeance measuring jig.

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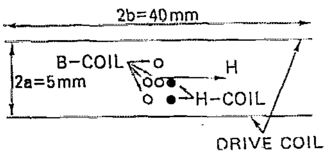

FIG. 3. Cross section perpendicular to the drive current of the measuring jig in Fig. 2.

fier with a sample, G_h = transfer function from the H coil to the sense amplifier with a sample, and V_{b0}, V_{h0}, G_{b0}, and G_{h0} are the values of V_b, V_h, G_b, and G_h when no sample is in the B coil.

Since the network analyzer can resolve the phase response, the measured permeability is in complex form.

IV. ACCURACY

A. Low-frequency region

Errors in the low-frequency region result from (a) the difference between the real area of the H coil and that used in Eq. (1), (b) the difference between the magnetic field in the H coil and that in the sample, and (c) system noise.

(a) Figure 3 is a cross section of the measuring jig perpendicular to the drive current. The theoretical magnetic field H at the center of the jig is given by

$$H=(2/\pi)J\tan^{-1}(b/a), \tag{2}$$

where J = current density and a,b = dimensions of the drive coil (see Fig. 3). For example, if a drive current of 1.78 mA (J = 44.5 mA/m) is applied to the drive coil, we have an H of 41 mA/m (0.51 mOe). The actual voltage induced in the H coil was measured, and an H of 41.6 mA/m (0.52 mOe) was obtained. Therefore, the actual area of the H coil is sufficiently close to that used in Eq. (1).

(b) Figure 4, which was derived using the two-dimensional finite-element method, shows the ratio of the average magnetic field in the H coil to that in a sample as a function of the permeability of the sample, with its thickness as a parameter. The ratio increases as the permeability or thickness of the sample increases as shown in Fig. 4. Since thicknesses of interest are less than or equal to 200 nm, the error caused by the ratio is considered negligible. A more rigorous analysis would consist of a three-dimensional solution to account for the finite width of the coils and sample. However, the relatively small errors in neglecting this effect are not included in this treatment.

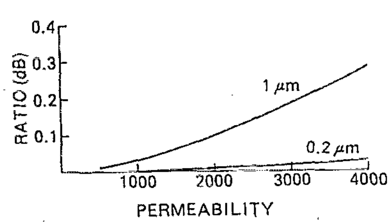

FIG. 4. Ratio of the average magnetic field in the H coil to that in a sample with its thickness as a parameter. This was calculated using a two-dimensional finite-element method.

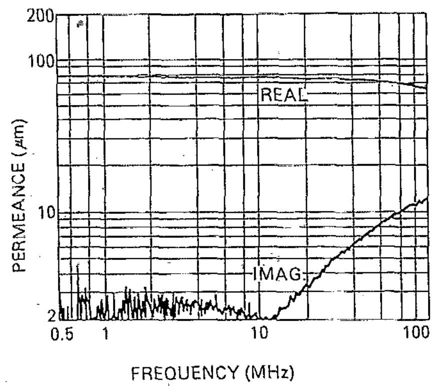

FIG. 5. Resolved permeance of an Fe-Si-Al-N film 50 nm thick. The upper trace is the real part and the lower is the imaginary. A drive current of 8 mA was applied.

(c) The noise in the sense amplifier was measured with a spectrum analyzer and was less than 1 nV/$\sqrt{\text{Hz}}$ over the entire spectrum of interest. The sense amplifier noise accounts for almost all the system noise because the thermal noise due to the resistance of the sense coils is much smaller. Measurements on a sample using a network analyzer resolution bandwidth of 300 Hz resulted in system noise less than 17 nV rms.

Figure 5 shows the measured permeance spectrum of an Fe-Si-Al-N film 50 nm thick with a drive current of 8 mA. As in Fig. 5, the film has a permeance of about 80 μm in the low-frequency region, and the resolved real permeance spectrum shows little fluctuation. If a sample with a permeance of 20 μm were measured with a drive current of 32 mA, the fluctuation would be the same as in Fig. 5 because the S/N ratio would be the same. The S/N ratio would be more than 36 dB at 1 MHz, because the induced voltage in the B coil would be 1150 nV. Since the instrument can supply a maximum drive current of 32 mA, it is possible to measure samples with a permeance of 20 μm with an S/N ratio of more than 36 dB at 1 MHz.

B. High-frequency region

Figure 6 is an example of the G_b/G_h response in Eq. (1). Obviously, this is not equal to 1 in the high-frequency region. If G_b/G_h is not taken into consideration, the measured permeance will include errors in the high-frequency region. Furthermore, G_b/G_h changes with the permeance of the sample. Since the equipment monitors the transfer functions with each sample and compensates the measured permeance using these functions, the errors can be reduced with our proposed approach.

The remaining error is a result of self-resonance in the sense coils. The self-resonance frequency was measured using an impedance analyzer and was about 500 MHz for the B coil and more than 500 MHz for the H coil. The influence of self-resonance is probably very small over the frequency range examined.

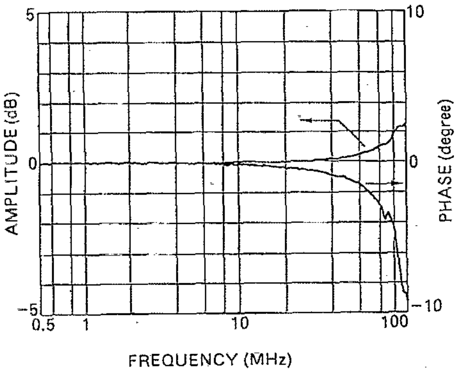

FIG. 6. An example of the amplitude and phase of the G_b/G_h of Eq. (1). This changes with the permeance of the sample.

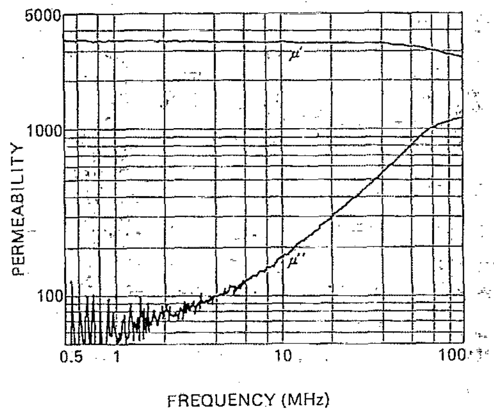

FIG. 7. Complex permeability of an Fe-Si-Al-N film 200 nm thick for perpendicular magnetic recording heads.

V. APPLICATION

We have developed high-performance Fe-Si-Al-N films for perpendicular magnetic recording heads by means of the dc magnetron sputter method.[4] Figure 7 is an example of the measured complex permeability of an Fe-Si-Al-N film 200 nm thick. The drive current is 2.5 mA. M_s and H_c were measured using a vibrating-sample magnetometer and were 1.35 T (13 500 G) and 22 A/m (0.28 Oe), respectively. The film has a real permeability of 3500 with a − 1-dB frequency of about 80 MHz. The real permeability fluctuates little in the low-frequency region, although the drive current is very small. A perpendicular magnetic recording head with this film will produce good performance in high-frequency recording as in HDTV VTRs.

VI. CONCLUSION

A high-performance permeance meter has been developed which has a frequency range of 0.5–120 MHz and with which it is possible to measure samples with a permeance of 20 μm with an S/N ratio of more than 36 dB at 1 MHz. The accuracy of the instrument is discussed. For one film of interest examined by us, the resolved real permeance spectrum fluctuates little in the low-frequency region, and the proposed approach can reduce error in the high-frequency region.

ACKNOWLEDGMENT

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