ECC Media Technology

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1. Introduction

Two years have already elapsed since Fuji Electric began mass-producing perpendicular magnetic recording media, and now perpendicular media accounts for a majority of Fuji's manufactured media. Areal density levels had stagnated at slightly more than 100 Gbits/in^2 with the longitudinal recording system, but progress is being made in the transition to perpendicular recording, and HDDs having areal densities on the order of 250 Gbits/in^2 are presently being mass-produced. Meanwhile, laboratory demonstrations of areal densities greater than 500 Gbits/in^2 have been reported, and areal densities are increasing at an annual rate of approximately 40% in mass-production and in the laboratory. Assuming that HDD areal densities will continue to increase at this rate, areal densities will reach 500 Gbits/in^2 in mass-production and 1 Tbits/in^2 in the laboratory during 2009. These types of high areal densities will be extremely difficult to realize by enhancing only the existing perpendicular media, and some sort of technical breakthrough is needed.

In order to increase the areal density, the track width must be reduced and the bit length shortened. To reduce the track width, the magnetic pole width of the recording head is made narrower, but this causes the recording field to decrease. Increasing the saturation magnetization B_s of the soft magnetic material used at the magnetic pole tip causes the recording field to increase, but the B_s value of the presently-used material is already approaching its theoretical limits and therefore this approach is not desired. In other words, with an increase in areal density, the recording head is predicted to become unable to perform write operations. On the other hand, in order to shorten the bit length, the magnetic reversal unit of the recording layer in the media must be reduced, but a smaller magnetic reversal unit leads to lower thermal stability. Namely, there is increased risk of erasing stored recorded data. Thus, to ensure thermal stability even when the magnetic reversal unit is small, the anisotropy of the magnetic material used in the recording layer may be increased. If anisotropy is increased, the magnetic field required for the recording, i.e., the switching field, will be increased further. As described above, an increase in the recording field of the head cannot be expected in the future, and therefore increasing the switching field of the media will cause the head to become unable to perform write operations. Thus, the three properties of "higher density", "write-ability" and "thermal stability" are difficult to achieve simultaneously, and this problem is known as the "tri-lemma of perpendicular media." The reason for mentioning the necessity of a breakthrough at the beginning of this paper is because a solution to this tri-lemma is thought to be difficult to achieve by extending the conventional implementation.

To solve this tri-lemma and realize higher densities, several candidate technologies including thermal assist recording and patterned media have been mentioned, and one such possibility having been proposed is ECC (exchange-coupled composite) media.[1] The results of simulations have been reported[2] as realizing up to the 1 Tbits/in^2 level, and show promise for the next-generation technology. Moreover, unlike thermal assist recording which requires that the head be equipped with a heat source and patterned media which requires that each bit must be physically segregated by microfabrication technology or the like, ECC media can be realized without any significant changes to the media or head, and is therefore highly advantageous from the perspectives of cost and manufacturing technology.

This paper describes the structure and features of ECC media and also discusses the development status of Semi-ECC media at Fuji Electric and future challenges for this media.

2. ECC Media

2.1 Principles and features of ECC media

Prior to discussing ECC media, we shall roughly estimate the media switching field when the specifications for 1 Tbits/in^2 level are satisfied. Using the same assumptions[2] as Greaves et al., and a crystal grain size of approximate-

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ly 6.5 nm which is the magnetic reversal unit, a magnetic layer thickness of 13 nm, and a K_uV/kT value of approximately 60 (where K_u: uniaxial anisotropy constant, V: activation volume, k: Boltzmann's constant, T: temperature), a simple computation of K_u yields a value of approximately 5×10^6 erg/cm^3. Here, by setting the saturation magnetization M_s of the magnetic crystal grains to 750 emu/cm^3, the switching field in consideration of the demagnetization field can be roughly approximated as ranging from H_0 to 17 kOe. This is much larger than the switching fields of media presently being used in applications. It is also much larger than the 12 to 13 kOe magnetic field of the head considered with the method of Greaves et al.[(2)], and therefore recording cannot be accomplished with these specifications. Consequently, we concluded that media which satisfies the 1 Tbits/in^2 level specification cannot be manufactured with a simple structure. The thermal stability must be maintained while the switching field is reduced, and ECC media, with which this is feasible, is described below.

Figure 1 shows a schematic drawing of ECC media. The recording layer of the ECC media is constructed from 3 layers: a soft layer, a hard layer and a layer for controlling the exchange coupling energy between these layers. In the case of an ordinary laminated film, the soft layer and hard layer would be directly laminated together, but the provision of an interlayer between these soft and hard layers and suitable control of the exchange coupling energy enable the switching field to be decreased without decreasing the thermal stability.

Figure 2 shows the simulated interlayer coupling energy dependency of the switching field H_{sw} and the energy barrier E_b/kT. This calculation, similar to the method of Inaba et al., uses a simplified 2-spin model that sets a single spin for each magnetic layer for 1 grain. In the figure, the horizontal axis shows that coupling becomes weaker as the interlayer coupling energy approaches 0, and that the coupling becomes stronger as the interlayer coupling energy increases. For example, in the case of direct coupling without an inserted interlayer for controlling the coupling energy between layers, the characteristics become similar to those on the right edge of the figure, and in the case where the interlayer coupling is completely cut-off, the characteristics are as shown for an interlayer coupling energy of zero. Moreover, the figure shows that thermal stability increases as the energy barrier becomes larger. From Fig. 2, it can be seen that as the interlayer coupling energy is increased from 0, the switching field drops once and establishes a minimum, and then rises again and eventually saturates.

At its minimum value, the switching field falls to approximately one-half the value as at the time of direct coupling, and since the energy barrier does not change at this time, we found that the switching field could be reduced without changing the energy barrier. In other words, an easy-to-record media that maintains its thermal stability was realized. The control of interlayer coupling energy in the region indicated by arrows in Fig. 2 is important for obtaining these types of results with ECC media.

Fig.1 Schematic diagram of ECC media

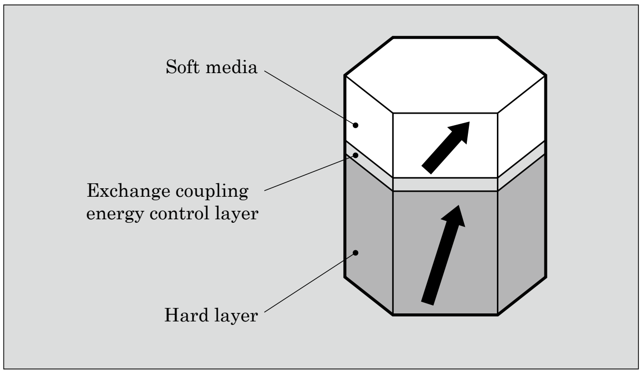
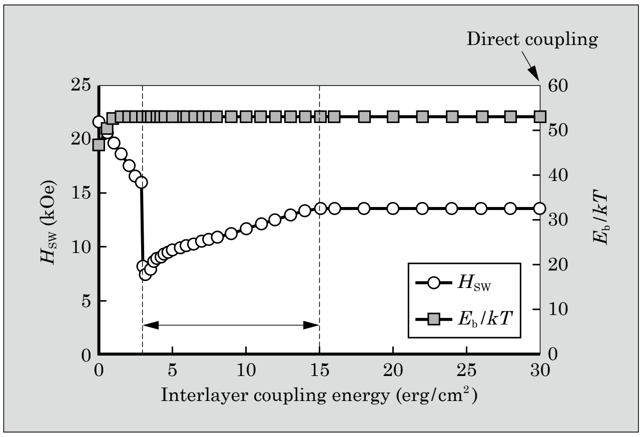


Fig.2 Exchange coupling energy dependency of switching field and energy barrier



2.2 Semi-ECC media

To fully utilize the advantages of ECC media and achieve high areal density, the following two measures are necessary.

(a) Increase the K_u of the hard layer (for example, set the K_u to at least 10^7 erg/cm^3)
(b) Increase the thickness of the soft layer (for example, set the thickness of the soft layer to at least half of the total thickness of the recording layer)

The reasons for the above are as follows.

(a) When the K_u of the hard layer is increased, thermal stability will increase, but the switching field will also increase.
(b) Increasing the thickness of the soft layer enables the switching field to be reduced significantly.

However, the following challenges exist.

(a) A practical magnetic material having a high K_u value and low noise and that satisfies requirements has not been found.
(b) Increasing the thickness of the soft layer is technically difficult.

Fig.3 K_u^{soft} dependency of minimum switching field and energy barrier

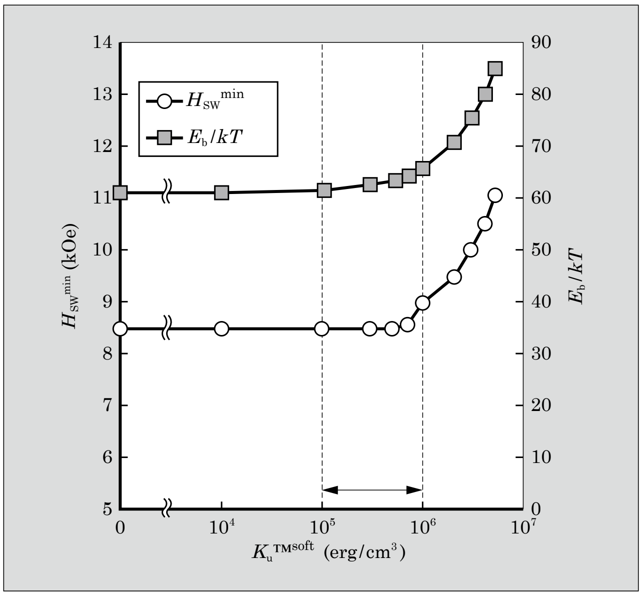


Fig.4 Kerr loop of Semi-ECC media

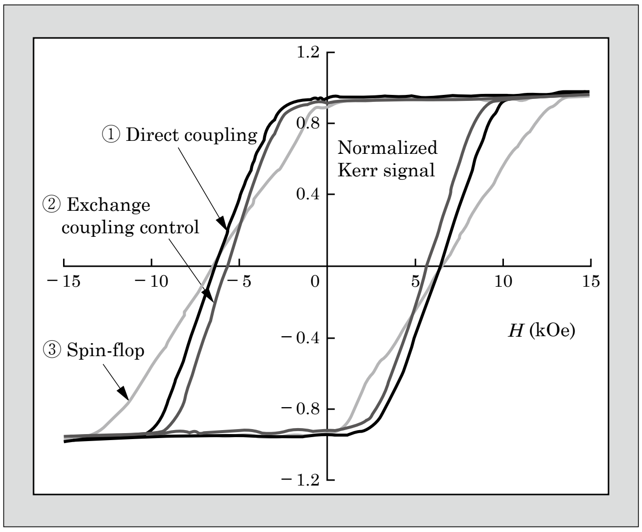
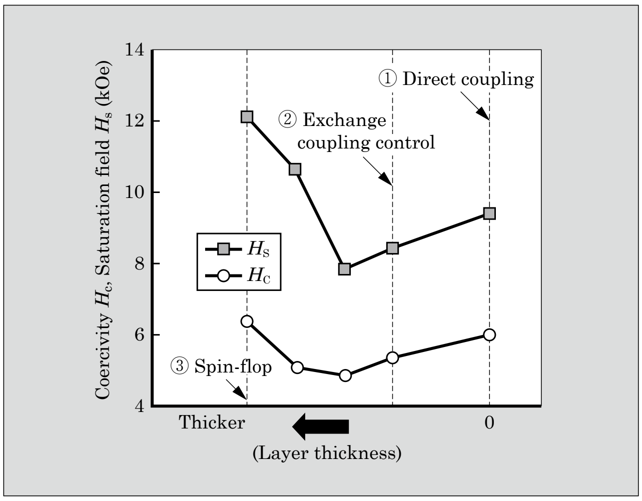


Fig.5 Coupling layer thickness dependency of H_c and H_s



Thus, as a step toward a transition to ECC media, we examined media structures that do not use a soft layer.

Figure 3 shows K_u^{soft} dependency of the soft layer on the minimum switching field H_{sw}^{min} and energy barrier E_b/kT. The minimum switching field is shown as the switching field (Fig. 2) that becomes a minimum when the interlayer coupling energy is changed. Moreover, here, the hard layer K_u is set to 6×10^6 erg/cm^3, which is a value that can be realized even with a CoPtCr-SiO_2 granular magnetic layer[(3), (4)]. From Fig. 3, it can be seen that even when not using a completely soft magnetic layer with a soft layer K_u of 0, as long as $K_u^{soft} < 5 \times 10^5$ erg/cm^3, then there will be no change in the minimum switching field and the energy barrier. Moreover, both the minimum switching field and the energy barrier exhibit a sudden tendency to increase for values of $K_u^{soft} > 1 \times 10^6$ erg/cm^3. These results demonstrate that the selection of a semi-hard layer with a K_u^{soft} of 1×10^6 (erg/cm^3) as the soft layer enables ECC media that does not exhibit a large increase in the switching field and has only a slight increase in the energy barrier to be obtained. Fuji Electric calls this Semi-ECC media and is working to advance its development. Chapter 3 describes characteristics of actual prototypes of Semi-ECC media. Hereinafter, the layer provided between magnetic layers and that controls the coupling energy (Fig. 1) is referred to as the coupling layer.

3. Characteristics of Semi-ECC Media

3.1 Magnetic characteristics

Figure 4 shows the changes in the Kerr loop when the coupling layer thickness is changed, and Fig. 5 shows the coupling layer thickness dependency of the coercivity H_c and saturation magnetic field H_s. Here, the K_u values of the hard layer K_u^{hard} and $K_u^{semi\text{-}hard}$ of the semi-hard layer are approximately 5×10^6 erg/cm^3 and 1×10^6 erg/cm^3, respectively, and the composition and thickness of the magnetic layers are constant so that only the thickness of the coupling layer is changed. So as to correspond with Fig. 2, Fig. 5 is plotted with the coupling layer thickness set to zero for direct coupling, and the coupling layer thickness increasing along the horizontal axis in the direction toward the left side. The interlayer coupling energy increases along the horizontal axis in the direction towards the right side, and corresponds to Fig. 2. Moreover, the Kerr loops assigned numbers ①, ② and ③ in Fig. 4 correspond to the same numbers shown in Fig. 5. These results showed that if the interlayer coupling energy increases, i.e., if the coupling layer thickness decreases, then the switching field (at the level matching H_s) of the prototype Semi-ECC media falls once to reach a minimum value and then increases, and exhibits the same behavior as that predicted by simulation. Moreover, it can be seen that in the case of direct coupling (①) and in the case where the interlayer coupling energy is controlled to near the minimum of the switching field (②), there are no significant differences in the shape of the Kerr loops, but in the region (③) where H_c and H_s increase dramatically, the Kerr loop assumes a two-step configuration, and its slope is also small (Fig. 4). In ③, at the region of the step, the magnetization of the semi-hard layer is believed to switch reversibly, and as a result, the switching field does not fall sufficiently. In Fig. 2, in order to increase the switching field in a region where the interlayer coupling energy is low, i.e., in a region of weak coupling (interlayer coupling energy < 3 erg/cm^2), a magnetization reversal process as in ③ is implemented.

These findings demonstrated the feasibility of manufacturing Semi-ECC media having the magnetic characteristics predicted through simulation. Therefore, next, we evaluated the read-write (R/W) performance and investigated whether write-ability and other characteristics had actually been improved.

3.2 R/W performance

Here, as in section 3.1, samples were manufactured without changing the composition and thickness of the magnetic layers, and with only the coupling layer thickness being changed. Since the write performance clearly deteriorates in a spin-flop state (③ of Figs. 4 and 5), this time, the thickness of the coupling layer was controlled so as to remain in a spin-flop free region on the Kerr loop.

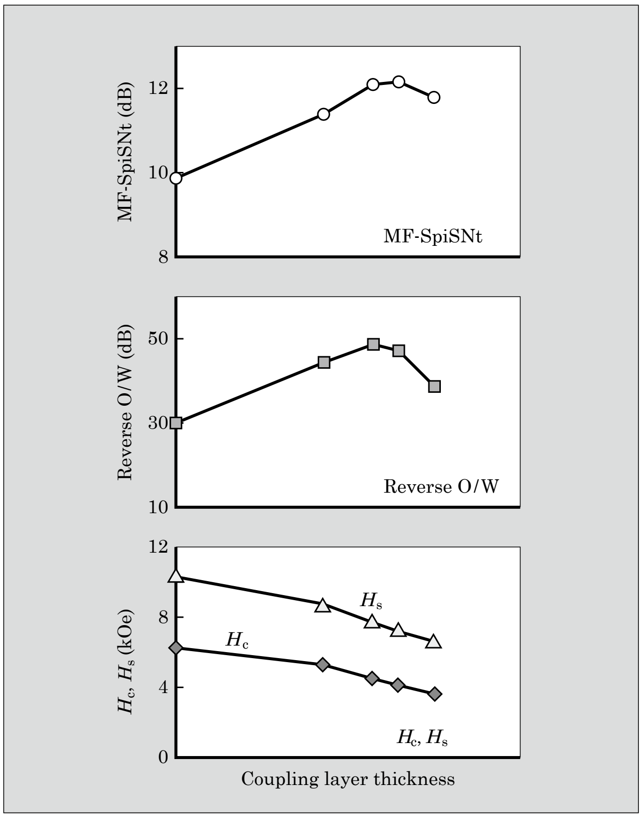
Figure 6 shows the coupling layer thickness dependency of magnetic characteristics and R/W performance of the prototyped Semi-ECC media. Here, the coupling layer thickness increases along the horizontal axis in the direction to the right side. The magnetic characteristics in Fig. 6 show that H_c and H_s steadily decrease as the coupling layer thickness increases from the directly coupled state. This corresponds to the region extending from ① to ② in Fig. 5. At the maximum, H_c decreases by approximately 2.6 kOe (41%) and H_s decreases by approximately 3.6 kOe (35%), and a strong effect on "write-ability" is obtained. On the other hand, as the coupling layer thickness increases, although H_c and H_s steadily decrease, it can be seen that both the reverse overwrite (R-O/W: overwriting high density recorded data with low density data) and MF-SNR (middle frequency signal-to-noise ratio) have a tendency to increase up to a maximum value and then to decrease. At the maximum, R-O/W and MF-SNR are improved by approximately 20 dB and 2.3 dB, respectively, and a strong effect on R/W performance was verified. These results demonstrate that the adoption of a Semi-ECC structure leads to improvement in not only the magnetic characteristics but also the R/W performance.

The reasons for differences in the magnetic characteristics and R/W performance when using coupling layer thicknesses in this region could not be clarified, but are presumed to be caused by the following.

(a) With Kerr loop measurements obtained using measuring times of approximately 30 seconds, noticeable steps and the phenomenon of increasing H_s were not observed. This is believed to be caused by successive reversals that occur due to the influence of thermal fluctuation of the two layers sandwiching the coupling layer.

(b) During extremely short time periods on the order of several nanoseconds, however, such as when recording with the head, thermal fluctuations have little effect and therefore a magnetic reversal behavior different from that during measurement of the Kerr loop is exhibited. In other words, there is the possibility that spin-flop states are being created dynamically.

Fig.6 Coupling layer thickness dependency of magnetic characteristics and read-write performance

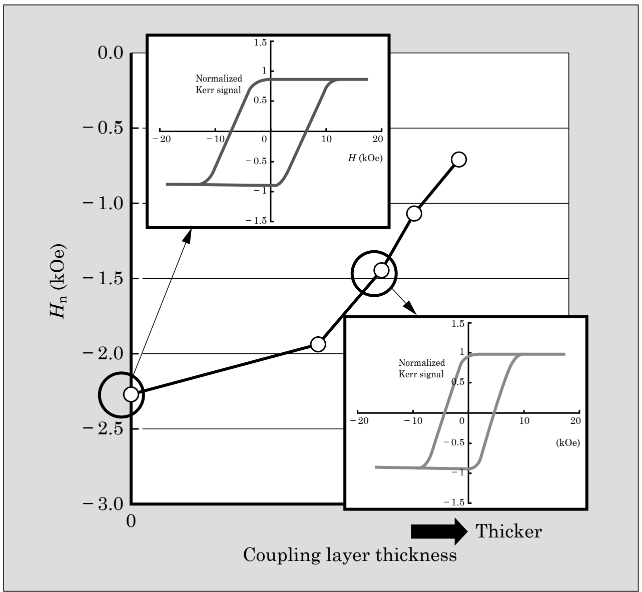


In closing, the following section describes future challenges to be overcome in order to produce Semi-ECC media suitable for use in practical applications.

3.3 Future challenges

Figure 7 shows the coupling layer thickness dependency of the nucleation field H_n in the Semi-ECC media that exhibited the R/W performance described in section 3.2 above. H_n corresponds to the "shoulder" portion of a Kerr loop, and the larger the overhang on the minus side, the higher tolerance to the thermal fluctuation and stray fields. Similar to the tendencies

Fig.7 Coupling layer thickness dependency of H_n



of H_c and H_s in Fig. 6, Fig. 7 shows that the absolute value of H_n decreases as the coupling layer thickness increases. Under the conditions in which R-O/W and MF-SNR are at maximum values in Fig. 6, H_n is only approximately −1.5 kOe and is insufficient in consideration of the thermal stability and a resistance to stray fields. In order to ensure a suitable value of H_n, increasing the K_u of the hard layer is effective, but as described above, it is not easy to increase the K_u in material that is suitable for practical use and exhibits noise low. Moreover, in addition to the specific challenge of ensuring a suitable H_n value in Semi-ECC media, achieving higher density presents several other challenges. The future challenges are enumerated below.

(a) Ensure a suitable H_n value
(b) Search for low-noise and high K_u magnetic material, or improve a process to realize lower noise in high K_u material
(c) Refine the magnetic layer crystal grain size or magnetic reversal unit

4. Postscript

A prototype of Semi-ECC media was manufactured, and a reduction in the switching field and an improvement in R/W performance were verified. In order to attain a level suitable for practical application, however, challenges clearly remain. Fuji Electric intends to overcome these remaining challenges through searching for suitable materials and improving manufacturing processes. In addition to the Semi-ECC structure, Fuji Electric is also verifying the excellent R/W performance that can be obtained from a laminated structure[4] provided with a K_u gradient. We also want to investigate new layer structures, such as a combination of this laminated structure and Semi-ECC.

References

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Glossary Hard layer and soft layer, Kerr loop, Reverse O/W and MF-SpiSNt

■ Hard layer and soft layer

The hard layer performs the role of stabilizing the recording, and is formed from permanent magnet material having a high coercivity H_c. Meanwhile, the soft layer performs the role of facilitating the recording, and is formed from material having a low H_c and relatively large permeability. ECC media suitably adjusts the coupling force between these layers to combine the attributes of both.

■ Kerr loop

When the surface of magnetized material is exposed to linearly polarized light, the polarization plane of the reflected light rotates. This is known as the magneto-optical Kerr effect (MOKE). The rotation angle is proportional to the magnitude of the magnetization, and therefore, a loop resembling the magnetization curve can be obtained by measuring the rotation angle while applying an external field. This is known as the Kerr loop. For perpendicular magnetic recording media, measurement of the magnetization curve is difficult due to the effect of a soft underlayer (SUL), and therefore the MOKE, which can be measured in a nondestructive manner, is often used to evaluate magnetic characteristics.

■ Reverse O/W and MF-SpiSNt
(Explanation of vertical axis of Fig. 6 on page 20)

Reverse overwrite (R-O/W) is the ratio of the record signal and erase signal strengths when overwriting on low density data high density recorded data. Higher R-O/W values indicate better “write-ability.”

MF-SpiSNt is the signal-to-noise ratio at one-half the maximum recording frequency. Higher MF-SpiSNt values indicate that bits can be recorded at higher densities.