Head Disk Interface Technologies for High Recording Density and Reliability

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Various technologies are being developed to simultaneously achieve a high-density storage capacity and high-reliability in hard disk drives. Some examples are technologies for reducing the gap between the head and magnetic layer of the disk while providing an accurate grasp of the conditions at the nano level and technologies for controlling the head's flying height at the nano level. Fujitsu is developing these technologies to improve the storage density and reliability of hard disk drives. In this paper, we describe the following Head Disk Interface technologies: a Co-Axial Impact Collision Ion Scattering Spectroscopy technique for evaluating the coverage properties of lubricants, technique for evaluating the coverage properties of the overcoats used on magnetic storage devices based on the Drop method, and a chemical treatment technology for the flying surface of the head slider.

1. Introduction

To increase the areal recording density of a hard disk drive (HDD), we need to reduce the gap between the head and the magnetic layer of the disk. The head/disk interface consists of a diamond-like carbon (DLC) overcoat on the disk and head to protect the surface of the magnetic layer, a lubricant film on top of the disk overcoat, and the head's flying height, which is currently about 10 nm. Each of these interface components significantly affects the storage density of an HDD (**Figure 1**).

This is why each interface component is downsized in each new generation of HDDs. We have come to the point where the lubricant film thickness is in the region of 1 nm, the disk medium overcoat thickness is in the region of 4 nm, and the flying height is in the region of 10 nm. We can liken the flying head to a jumbo jet flying several millimeters above the ground. If contaminants such as cyclic siloxane are adsorbed to the head at a height of several molecules, they will cause the head and disk to come into contact and destabilize the head's flight. Moreover, the lubricant film on the disk overcoat consists of one to two layers of fluorine macromolecules, and if cohesion between several of these molecules occurs on the disk, it will greatly affect the flight stability. In addition, if the overcoat is made thinner, the coverage limit of the film is reduced, leading to corrosion of the underlying magnetic film.

The technology concerning phenomena related to the gap between the head and disk is referred to as Head Disk Interface (HDI) technology. To improve the recording density and reliability of HDDs, Fujitsu has developed methods for evaluating these phenomena at the nano level and technologies to ensure stable flight.

In this paper, we describe recent HDI technologies for the following: evaluation of the coverage properties of lubricants using Co-Axial Impact Collision Ion Scattering Spectroscopy (CA-ICISS), quantitative evaluation of defects in the overcoat using Inductively Coupled Plasma-Mass

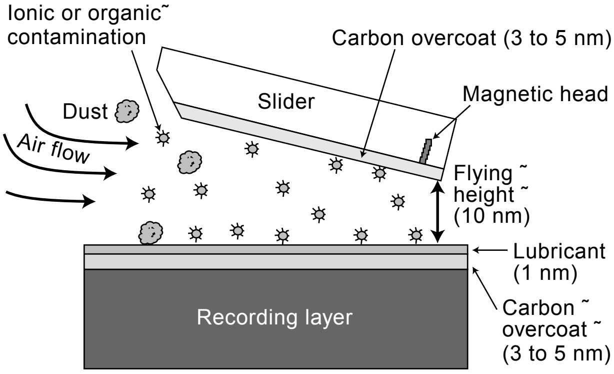


Figure 1
HDD head and disk medium configuration.

Spectrometry (ICP-MS), and achievement of stable flight by chemically treating the slider's flying surface.

2. Utilization of CAICISS to evaluate coverage properties of lubricants

In this section, we describe the CAICISS technique, which is used to evaluate the coverage properties of lubricants. To achieve ideal adhesion of lubricant molecules, the lubricant should be spread out evenly in a single molecular layer with the polar end group intended for adsorption oriented toward the substrate. However, if uneven coverage occurs because of lubricant aggregation or poor orientation of the polar end group toward the substrate, the unstable head flight mentioned above or other phenomena will greatly affect the reliability of the HDD.

Coverage control of the lubricant is therefore extremely important when an improvement in the corrosion resistance and satisfactory HDI characteristics have been achieved. However, because the lubricant film is now in the exceedingly thin 1 nm region, it is difficult to evaluate its coverage properties using conventional techniques. We therefore developed a new technique for evaluating these characteristics using CAICISS, which is a non-destructive technique with high surface sensitivity.

With the CAICISS technique, the target sample is exposed to a low-energy He ion beam energized to the order of several keV. Elemental analysis of the surface is then performed based on the change in energy of the He ions that are backscattered to approximately 180 degrees. Compared with other spectrum techniques, CAICISS has the advantage of a high surface sensitivity. However, because there is a high probability that keV-order ions are neutralized when they collide with the target sample, it is difficult to obtain a sufficient detection sensitivity when using a standard energy detector. We resolved this problem by using a Time of Flight (TOF) detector.

Using CAICISS, we can evaluate the coverage properties of the lubricant from the chemical composition of the DLC underlayer and from the surface chemical element (lubricant) ratio. However, if the same element is included in both layers, it becomes impossible to judge which layer an instance of that element belongs to. To make the combination of lubricant and DLC applicable to this case, we focused on the composition of the main-chain part of the lubricant [-$(C_2F_4O)m(CF_2O)n$-] for use in evaluating the coverage properties of lubricants.

Although there are differences in the polar end groups of the different types of lubricants that are applied to magnetic media, the main-chain perfluoropolyether (PFPE) compositional ratio is constant; that is, the fluorine-to-carbon atomic ratio (F/C ratio) for lubricants of any molecular weight is always 2. On the other hand, DLC is usually composed of carbon and hydrogen, but due to fundamental constraints, the elements that can be detected by CAICISS using He ions as probes are those that are higher than the He mass number, which means that the only applicable element is carbon. Therefore, although the intensity of the carbon signal obtained from CAICISS measurement is derived from both the lubricant and the DLC, because the reduction from the nominal value of 2 in the F/C ratio given by Equation (1) is clearly due to the DLC, the coverage properties of the lubricant can be evaluated by comparing the F/C ratio obtained from the calculation using ZBL approximation:[1)]

$$\frac{F_{\text{Lub}}}{C_{\text{Lub+DLC}}} \leq 2 \qquad (1)$$

where F and C represent the number of fluorine atoms and carbon atoms, respectively.

The lubricants that we evaluated (Fomblin series manufactured by Solvay Solexis) were applied to magnetic media comprising layers up to the DLC layer using the Dip method, and the thickness of the film was controlled by adjusting the concentration of the lubricant solution and the speed at which the media was lifted out of the lubricant solution. TALIS-9700 manufactured by Shimadzu Corporation was used for CAICISS measurement, and the measurement parameters were He for the incident ions, an acceleration voltage of 2 keV, and an accumulation time of 120 s.

The spectral changes with respect to the thickness of the AM3001 lubricant film spread on the disk are shown in **Figure 2**. The y-axis in this figure shows the backscattered intensity of He ions, and the x-axis shows the time of flight. The higher the mass number of the chemical element, the shorter the time of flight of He ions. Therefore, the three peaks in the lower half of the TOF axis can be attributed to fluorine, oxygen, and carbon. As the thickness of the film increases, the intensity of the fluorine increases, but the intensity of carbon decreases. This behavior is directly influenced by the process of coating the DLC surface with lubricant.

Figure 3 shows the F/C ratio versus film thickness for the AM3001 and Z-TETRAOL lubricants using this method as determined from the intensity of fluorine and carbon obtained by subtracting the background.

If we look at the AM3001 lubricant, the F/C ratio increases with the film thickness. An F/C ratio of 2 is achieved at a thickness of 1.5 nm, and this can be regarded as the lower limit of film thickness required to achieve complete coverage of the surface with this lubricant. The Z-TETRAOL curve is similar to the AM3001 curve in that the coverage properties improve as the lubricant thickness is increased. However, whether thick or thin, a Z-TETRAOL film has a higher

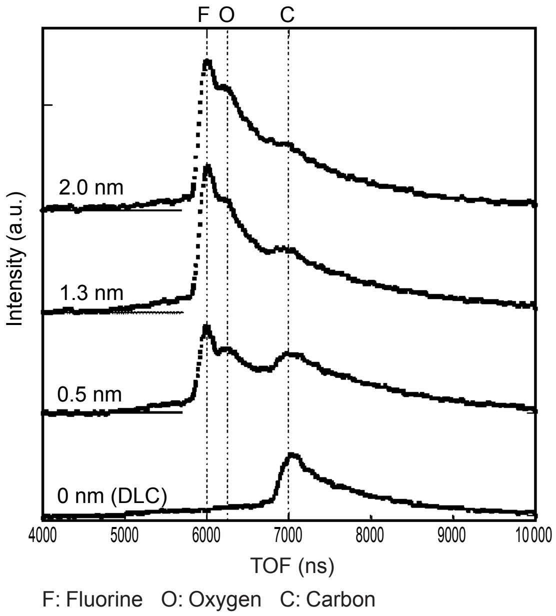


Figure 2
CAICISS spectra of AM3001 lubricant.

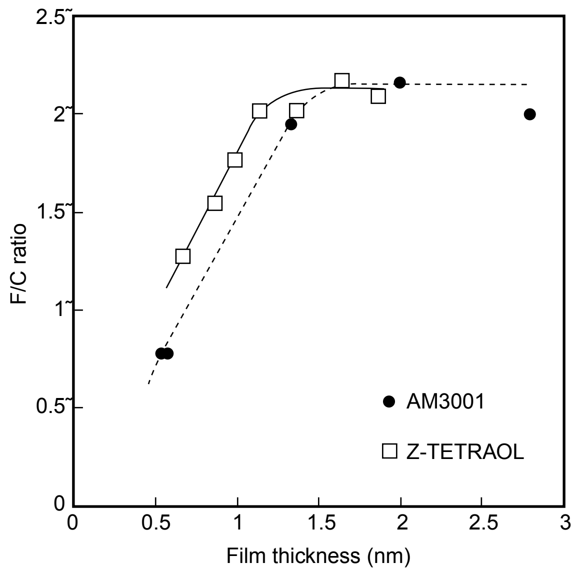


Figure 3
F/C ratio versus film thickness for AM3001 and Z-TETRAOL.

coverage than an AM3001 film of the same thickness. The high-orientation characteristics of the Z-TETRAOL lubricant occur because of a strong end-group adsorption force, so we can surmise that the coverage properties are improved by the high-orientation characteristics of the Z-TETRAOL lubricant.

As explained above, this method enabled us to evaluate the coverage properties of film lubricants at the molecular level, which is difficult to do with conventional techniques. Because the coverage properties of lubricants are key factors in determining the causes of flight damage and selecting suitable lubricants to enable low flight in future products, this method is expected to optimize process development.

3. Evaluation of overcoat coverage properties using ICP-MS: Drop method

If the DLC overcoat on the disk medium is too thin, the film and holes at the nano level become non-uniform, corrosion occurs in the magnetic layer, and the overcoat loses its protective function. A technique for correctly evaluating the properties of the film is therefore essential for achieving a DLC film thickness at the nano level. In this section, we introduce a technique for quantitatively evaluating the defects in an overcoat that is several nm thick. With this technique, an acid solution is dropped onto the surface of the DLC film, and then microanalysis is performed on the cobalt component of extracted samples. When a disk's magnetic film corrodes, there is water present where the coverage of the DLC film failed. This water causes electrochemical dissolution of the cobalt atoms in the lower magnetic layer.[2] This method of quantitatively evaluating the coverage properties of the overcoat is called the cobalt dissolution method.

Traditionally, the International Disk Drive Equipment and Materials Association (IDEMA) advocates the use of disk immersion (Dip method) in evaluations using cobalt dissolution. However, our investigations revealed several problems with this method. Specifically, because this method immerses the entire disk in the solution, we were particularly concerned about dissolution from the sides of the disk. As shown in **Figure 4**, we found that the amount of dissolution depended on the material used to cover the sides (tape or resin) and that the quality of this material greatly affects the measurement reproducibility.

Moreover, once the disk surface has been immersed, problems such as being unable to determine the cobalt distribution in the overcoat occur.

We therefore developed a new technique called the Drop method. In this method, we apply liquid to a fixed-size area on the DLC film and allow liquid drops to form by surface tension. A stable surface tension can be obtained because although the DLC film is exceedingly thin, it is given an exceedingly fine membrane structure for high durability. We use micropipettes to form a fixed number of drops at several locations on the

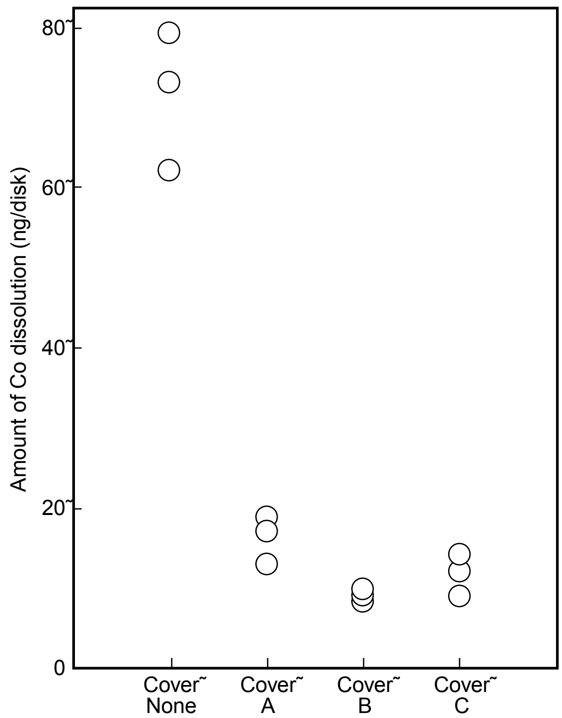


Figure 4
Variations in amount of dissolution depending on material used for sidewall covers.

disk's surface. These drops are left on the surface for a fixed period and then collected using pipettes or syringes and inserted into test tubes or similar items for measurement using ICP-MS. Evaluation of the coverage properties can be performed at further locations on the surface without any need to consider dissolution from the sides. However, because of the small amount of liquid that is extracted and the small amount of dissolved cobalt it contains, it was necessary to improve the extraction efficiency. After considering the dissolution behavior of the liquids extracted using the Dip method with nitric acid and hydrofluoric acid — which is even more corrosive — we found that the most suitable approach is to use 1 ml of 3% nitric acid.

The standard immersion time for the Dip method is 30 minutes. However, after noting the change in the amount of cobalt dissolution over time, we determined that the optimal delay before extraction for the Drop method is 60 minutes.

Figure 5 shows the cobalt dissolution rate over 60 minutes versus the DLC film thickness. As the DLC film becomes thinner, its coverage properties degrade, causing an increase in the amount of cobalt dissolution. From this result, we found there was almost a linear correlation in the amount of cobalt dissolution up to a DLC film thickness of 5 nm. **Figure 6** shows our results for the DLC film deposition conditions. It is well known that compared with Chemical Vapor Deposition (CVD), the sputtering deposition method provides a less pure DLC film and inferior coverage. Our cobalt dissolution results obtained from the Drop method show this quantitatively.

Thanks to the development of the Drop method, we can reduce the variations that occur with each measurement when compared with the conventional Dip method of cobalt dissolution analysis. Also, because of this method, we can now quantitatively assess the DLC film deposition conditions and the cobalt separation behavior. Furthermore, it enables us to measure the distribution of film properties on the surface of a disk. We believe the Drop method can become an important tool for evaluating the mass-production quality of magnetic disk media and the DLC overcoats of 3 nm or less that will be developed in the future.

4. Chemical treatment technology for head flying surface

It is well known that if the head's flying height falls below 10 nm, the Van der Waals forces between the head's flying surface and the disk exerts an influence on the head's ability to fly.[3)-5)] Therefore, we considered giving the head a low-energy flying surface to reduce the Van der Waals forces between the head and disk and thereby achieve satisfactory flying characteristics at heights below 10 nm. The surface energy of the perfluoropolyether medium lubricant is extremely small, and for practical uses, we considered that the flying characteristics could be

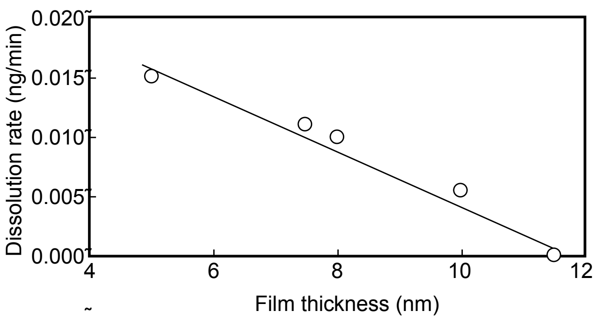


Figure 5
Cobalt dissolution rate versus DLC film thickness.

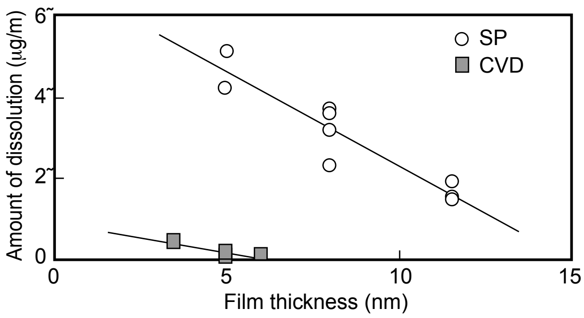
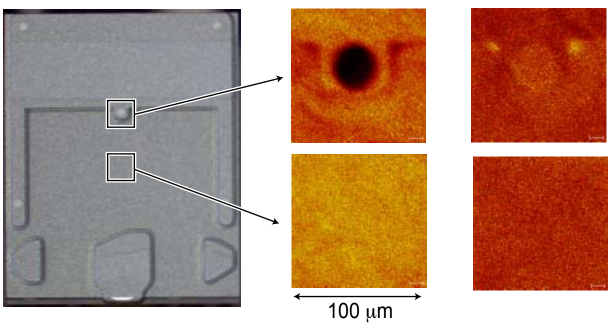


Figure 6
Cobalt dissolution amount versus DLC film thickness.

improved by lubricating the head's flying surface. However, as the lubricant flows on the head, it disturbs the surface stability; therefore, to maintain a stable surface, the lubricant must be strongly bonded to the substrate. We considered bonding the molecules in the lubricant to the substrate using ultraviolet light;[6),7)] this method is superior to conventional methods in that the lubricant can adhere directly to the DLC overcoat without being influenced by the functional end groups of the lubricant molecules.[8)]

We used a padded pico slider with a flying height of 12.5 nm for our flying head tests.[9)] The coverage of the lubricant that adhered to the head was evaluated qualitatively using time-of-flight secondary ion mass spectrometry (TOF-SIMS). The contact angle method was used to obtain the surface free energy. To evaluate the flight characteristics, we reduced the pressure in the chamber and then returned it to atmospheric pressure to reproduce the touchdown and takeoff air pressures and then converted them to altitude values for comparison. Our reasoning for using this unconventional method was that the higher the touchdown and takeoff altitudes, the higher the reliability. The Van der Waals forces between the head and disk were calculated using Equation (2).[10)] Here, A_{TFi}', D, T, and T' represent, respectively, the Hamaker constants for the multilayer configuration, the distance between the head and disk, the thickness of lubricant on the disk, and the thickness of lubricant adhered to the head surface.

$$P_{vdW} = \frac{1}{6\pi}\left\{\frac{A_{TF1}}{D^3} + \frac{A_{TF2}}{(D+T)^3} + \frac{A_{TF3}}{(D+T')^3} + \frac{A_{TF4}}{(D+T+T')^3}\right\} \quad (2)$$



(a) (b) Al^+ (c) $C_2F_5^+$

Figure 7
TOF-SIMS ion image mapping of head flying surface.

First, we performed image mapping of Al^+ and $C_2F_5^+$ ions using TOF-SIMS to evaluate the coverage of the lubricant adhered to the head. **Figure 7** shows the mapping results of the lubricant adhered to the head surface by ultraviolet light treatment. The ion count is indicated by color density: the lighter the image, the higher the ion count.

The figure also shows the presence of aluminum and lubricant on, respectively, the Al^+ and $C_2F_5^+$ ions that were detected. Again, the light areas of the image indicate an abundance of aluminum and lubricant. Figure 7 (b) shows mapped images of Al^+ ions. The upper image shows the pad area of the head, and the lower image shows the ion milling area, which is composed of an alumina titanium carbide (AlTiC) material. The black area is the DLC pad area: no Al^+ was detected in this area.

By using this method and then performing TOF-SIMS analysis, we can obtain information about the distributions of chemicals on the surface. The ionic strength of the $C_2F_5^+$ that comes from the lubricant molecule is of the same level in both the pad and ion milling sections, and we found that the lubricant adhered evenly over the entire upper head surface [Figure 7 (c)]. The surface free energy on the DLC layer of the head's flying surface was 40.3 mN/m when the surface was untreated. When the measurement conditions included a 1 nm lubricant film, the surface free energy was reduced to 28.3 mN/m.

Our calculations indicate that the lubricant film that adhered to the head's flying surface reduced the interaction between the head's flying surface and the disk surface (Van der Waals forces). The interaction between the surfaces us-

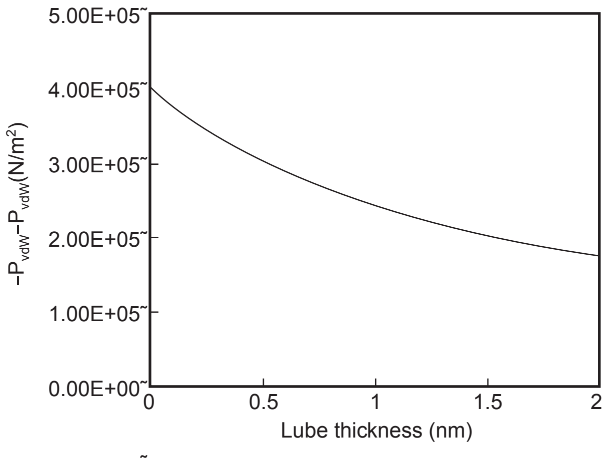


Figure 8
Van der Waals pressure versus thickness of lubricant adhered to head.

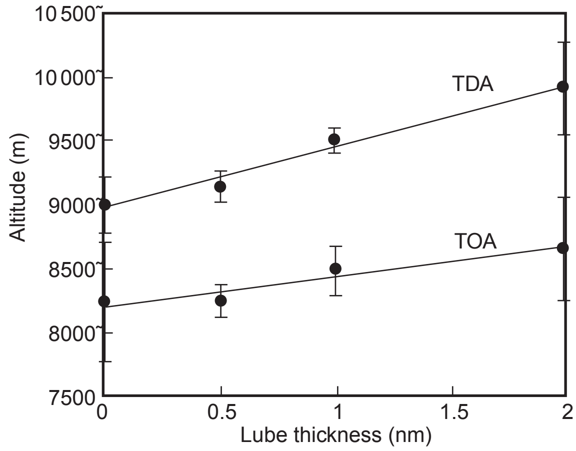


Figure 9
Touchdown and takeoff characteristics obtained from reduced pressure flying tests.

ing Equation (2) was obtained as the Van der Waals pressure PvdW, which is the Van der Waals forces per unit area. **Figure 8** shows the changes in Van der Waals pressure with respect to the thickness of the lubricant film adhered to the head's flying surface when the flying and disk surfaces are assumed to be parallel.

Currently, the flying gap D is fixed at 3 nm. Figure 8 shows that the Van der Waals pressure decreases with the thickness of the lubricant film adhering to the head's flying surface. This adherence is therefore expected to improve the head's flying height characteristics.

Figure 9 shows the touchdown altitudes (TDAs) and takeoff altitudes (TOAs) with respect to variations in the thickness of the lubricant film adhered to the head's flying surface. In this figure, the 0 nm film thickness indicates a non-treated (normal head).

As described earlier, the higher the touchdown and takeoff altitudes, the higher the reliability. In other words, the higher the touchdown and takeoff altitudes, the lower the touchdown and takeoff flying heights, which translates into a lower, more stable flying height. The touchdown and takeoff altitudes both increase with the thickness of the lubricant film adhered to the head. We found that adhering lubricant film to the flying surface to make it a low-energy surface is effective for improving the flight characteristics. As can be seen in the relationship between the thickness of adhered lubricant and the Van der Waals pressure shown in Figure 8, this improvement can be attributed to a reduction in the Van der Waals forces working between the head's flying surface and the disk.[11)]

5. Conclusion

In this paper, we described three HDI technologies in the nanotechnology realm for improving HDD recording density and reliability by stabilizing and reducing the physical gap between the magnetic layer of the disk and the head slider. These technologies enabled 1) the realization of film deposition without cohesion between the lubricant molecules; 2) a reduction in the thickness of the overcoat without causing defects at the nano level; and 3) a low flying height without impurities adhering to the head by suppressing the influence of the Van der Waals forces. As can be seen from the technical examples described in this paper, it is important to grasp what is happening at the nano level. From now on, to further reduce the gap between the head and the magnetic layer of the disk, the development of HDI technologies for the near-contact and contact realms will become essential. To achieve both high-density storage and reliability in HDDs, we believe that HDI technology development at the nano level will become increasingly important.

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