Flyability and Durability Test of Dynamic Fly-Height Sliders at 1 nm Clearance

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ABSTRACT

The requirement of higher storage density in hard disk drives pushes the head-to-media spacing (HMS) ever smaller. Currently, thermal protrusion at the transducer realized by the heating element in dynamic fly-height (DFH) sliders can be used to control the HMS by applying controllable electrical power. Thus, just how low the slider can fly stably and reliably using the DFH technology is a major concern for the hard drive industry. In this study, a 1 nm head-disk clearance flying of DFH sliders was achieved by making the protrusion back off 1 nm immediately after touchdown. Moreover, the flyability of the DFH sliders flying at 1 nm clearance was investigated by monitoring laser Doppler vibrometer (LDV), acoustic emission (AE) and friction signals. In particular, the durability of the head-disk interface at such a small spacing was evaluated by inspecting the lube pick-up on the slider air-bearing surface (ABS), carbon wear of sliders and disks and lubricant modulation/depletion after different durations of 1 nm clearance flying using optical microscopy, scanning electron microscopy (SEM) and the optical surface analyzer (OSA) respectively. Finally, the possibility of stable flying of DFH sliders at 1 nm clearance was verified experimentally.

KEY WORDS

Head-Disk Interface, Flyability, Durability, Contact, Wear, Dynamic Fly-Height

1. INTRODUCTION

To achieve a higher storage density in hard disk drives, the physical spacing between the read/write element and the disk surface must be decreased. For the next generation of hard disk drives with a density of 1 Tbit/in^2, a head–disk mechanical separation of 3.5 nm is estimated to be required and only 1.5 nm or less is left as the nominal clearance excluding the glide avalanche [1]. At such an ultra-small spacing, the intermittent/continuous contact at the head-disk interface (HDI) may occur, which may cause wear of the slider and/or disk and may affect the dynamic stability of the slider.

Flyability test [2] and many simulation works were carried out previously to study the HDI stability in close proximity. However, for the conventional slider, it is hard to fly stably at such a low FH due to the adhesive force between the slider and disk [3, 4]. Meanwhile, HDI durability in a contact condition was also studied extensively using a drag test or contact start-stop (CCS) test [5, 6]. But, the continuous contact regime is also difficult to achieve because of the contact-induced head bouncing and excessive heat and wear [1].

Recently, DFH sliders with a thermal actuator (or heater) have been proposed and introduced into commercial products [7]. The heater, when powered, causes the read/write element to protrude and effectively reduce the head-disk clearance and thus the HMS. In contrast with flying height (FH) reduction of the whole slider, the protrusion occurs only in the area around the read/write element and only when needed for reading or writing [8]. Therefore, it is a promising technique for achieving ultra-small spacing with small adhesive force or light contact and thus high record density. Thus, evaluation of the HDI performance at nanometer/sub-nanometer DFH clearance and determination of the clearance limit for stable and reliable flying of DFH sliders are major concerns for hard drive manufacturers.

In this study, a specially designed DFH slider for ultra-low FH was used to study experimentally its flyability and durability at an ultra-small clearance of 1 nm. First, the relationship between FH change and heater power of each slider was calibrated. Then, a series of flying tests at 1 nm clearance for incremental time durations were performed. Multiple techniques were used to monitor the contact and slider dynamics. The lube pick-up on the slider ABS, slider and disk carbon wear and lubricant moguls/depletion were also inspected after each test.

2. EXPERIMENTAL

A. Apparatus

All tests were performed on a VENA CSS & Load/Unload Tester that was specially designed for HDI test and is commercially available. A schematic of the experimental setup is presented in Fig. 1. The disk and head gimbal assembly (HGA) are installed on the spin-stand of the tester, which consists of a spindle, an arm actuator, a stain arm and a load/unload ramp. An AE sensor and a precision strain gauge are integrated in the arm to detect contact and measure friction between the slider and disk, respectively. Dual DSP-based motor controllers drive the spindle and the arm actuator. The waveform generator can apply a controllable voltage to the heater embedded in the slider while the data acquisition system is used to acquire the signal from the AE sensor and strain gauge. An external LDV is able to project the laser spot onto the backside of the slider through a hole in the flexure to measure its vertical vibration.

B. Samples

In this study, femto (0.85 mm by 0.7 mm) DFH sliders with the same ABS design (see Fig. 5) and 2.5” commercial disks were used. The disks have a glide avalanche of ~2.5 nm, an AFM roughness (Ra measured over 10 µm) of 0.3 nm, and they are coated with 3.5 nm diamond-like carbon (DLC) overcoat and 2.0 nm of Z-Tetraol lubricant with a bonding ratio of 35%. The sliders have a flying height of about 12 nm on the spinning disk at the test condition given in the next section.

C. Test Methods

In order to control the head-disk clearance, the relationship between the HMS change and heating power was calibrated first by measuring the HMS variations magnetically at a series of incremental heater powers using a Guzik test system which could capture the magnetic readback signal from the read transducer of the slider flying on a pre-written disk. This HMS measurement technique is based on the Wallace equation [9], where the change in amplitude of the measured read-back signal harmonics directly relates to the change of the spacing between the read/write transducer and the magnetic media [10]. Fig. 2 shows the measured HMS (or FH) reduction as a function of heater power. A 2nd order polynomial was used to fit the measured data. Also, using a basic equation of $P=V^2/R$, the conversion of voltage to power was done after the heater resistance was measured.

To find the actual clearance, however, a reference point where the spacing is known is needed. The reference point is usually the point where the head touches the disk [8]. In this study, each test slider was loaded onto the outer diameter (OD, 27.4 mm in radius) of a spinning disk at 5400 rpm and a linear speed of about 16 m/s. To obtain the 1 nm flying clearance between the head and the disk, touchdown (TD) was initiated of each slider first by gradually increasing the heater voltage (with the minimum voltage increment of 0.02 V). Simultaneously, the AE sensor and LDV were used to monitor the contact (shown in Fig. 3). When contact occurred, the power was reduced immediately and the TD voltage was recorded. Then the voltage needed for 1 nm back-off of the head pole-tip was calculated according to the calibrated equation in Fig. 2 and applied to the heater so that the slider would fly at 1 nm clearance.

To understand the flyability and durability of the DFH sliders flying at ultra-low FH, the virgin sliders were loaded onto virgin disks and flew at 1 nm clearance for different durations: 0 h (TD only), 0.5 h, 2 h and 15 h. During these tests, the AE sensor, friction gauge and LDV monitored the contact and slider vibration. After each test, the slider ABS was checked under a microscope to see if there was any lubricant on it. Also, the lubricant moguls/depletion and disk carbon wear were measured using an OSA. In addition, the slider carbon wear was inspected by a SEM.

3. RESULTS AND DISCUSSION

A. Slider Dynamics

The vertical vibration of each slider was monitored using the LDV. The vibration frequency spectra of the slider at initial FH (without heater power), when touchdown occurred, at the beginning of 1 nm clearance flying and after different durations of 1 nm flying are shown in Fig. 4. Also the surface modulation of the spinning disk on the location where the slider would fly is shown in Fig. 4. The spinning disk and the slider without power had similar vibration spectra, which indicated that the slider flew very well on the disk. When touchdown occurred, two peaks appeared suddenly in the high frequency region (250-300 kHz) which indicated that the contact induced slider bouncing occurred. But, the slider's flying recovered immediately to the previous stable state without the bouncing vibration after the 1 nm back off, and very little change was found in the frequency spectrum after 0.5 h, 2 h and 15 h of 1 nm clearance flying. The dynamics results revealed that all of the sliders were recoverable from slight contact and could fly stably over the disk at 1 nm clearance for up to 15 h flying.

B. Lube Pick-Up

Lube pick-up on the slider ABS may degrade the HDI stability through lubricant mediated adhesion [11]. At such a small clearance, significant lube accumulation on a slider surface is a serious threat to the HDI stability and durability. Therefore, the slider ABS was monitored carefully under a microscope after each test. Fig. 5 shows the ABS pictures of the sliders after 0 h (TD only), 0.5h, 2h and 15h of 1 nm clearance flying. All of the sliders looked very clean and no lube droplet was seen on their ABS, which indicated that there was little lube transfer or accumulation on the slider ABS during initial TD and flying at 1 nm clearance. Thus, lube pick-up was not an issue for the DFH sliders flying at 1 nm clearance in these tests.

C. Lube Modulation/Depletion

The lube thickness modulation is generated by slider-disk dynamic interactions, and is due to the slider body motions [12], which can affect the HDI performance to some extent. Fig. 6 shows the OSA Q-phase images of 1 mm wide sections of three disks. The Q-phase channel of the OSA is capable of sub-angstrom measurement of the lubricant thickness [13]. The bright area in these images represents thinner lubricant compared with the surrounding areas while the dark region stands for thicker lubricant. As shown in Fig. 6(a), TD could lead to obvious lube depletion (the straight bright band in the middle of the image) on the disk. But, when the slider flew at 1 nm clearance, the lube modulation or ripples dominated instead of depletion, shown in Fig. 6(b)-(c). The lubricant modulation shown in the images were mainly caused by the air-bearing shear force and slider vibration and the amplitude of it was only one or two angstroms. The lube modulation on all of the tested disks looked normal and there was no obvious increase in amplitude as the flying duration increased (from 0.5h to 15h), which demonstrated the interaction between slider and lubricant layer was not too severe at 1 nm clearance and could remain stable for a long time.

D. Slider DLC Wear

Contact between the slider and disk may wear the slider and disk and generate particles. The thickness budgets of the slider or disk overcoats for 1 Tb/in^2 hard drive is around 1 nm [1]. Any wear or scratch on the DLC layer beneath the read/write transducer may damage the magnetic head. Thus, it is essential to evaluate the slider wear after the durability tests. The SEM was used to detect the very light slider wear. The SEM images of the sliders after flying for 0 h (TD only), 0.5 h, 2 h and 15 h, respectively, at 1 nm clearance are shown in Fig.7. The lower portion of the image is the slider body, made of a composite of alumina (Al_2O_3) and titanium carbide (TiC), while the upper portion is the alumina basecoat, read/write elements, and encapsulation layer. The bright region in the upper portion is the location of the read/write transducers as well as the peak of the thermal protrusion, and therefore it is the most likely place to be worn. Fig. 7(a) shows that a few very light scratches appeared after transitory and slight TD, while Fig. 7(b)-(d) indicate that there was no obvious additional wear after a period (up to 15 h) of flying at 1 nm clearance. The results denote that the DLC wear on the slider surface is very slight, mainly caused by thermal protrusion TD and is independent of the flying duration at 1 nm clearance. Therefore, the flying of DFH sliders at 1 nm clearance should not cause significant wear on the slider DLC layer.

E. Disk Carbon Wear

Serious disk carbon wear caused by slider-disk contact can generate debris on the disk, damage the magnetic media and thereby lead to data loss. The OSA S and P polarized light reflectivity varies in different ways as a function of thickness of the disk lubricant and carbon overcoat. Both the S and P reflected light intensities increase in the case of carbon film thinning (or carbon film wear) [14]. Fig. 8 shows 1mm wide sections of two disks in S and P polarized light of the OSA. As shown in the figures, a very light carbon wear line was observed on both disks, one after only TD (Fig. 6(a)) and the other after TD and following 15 h of 1 nm clearance flying (Fig. 6(b)). However, the wear was not very clear and no significant additional wear was seen in Fig. 6(b) compared with Fig. 6(a). So the 1 nm clearance flying of DFH sliders didn't cause significant wear of the disk carbon film. Light wear observed on some disks is expected to also be initial TD related. For a detailed interpretation of the images, please refer to [14].

4. CONCLUSIONS

Flyability and durability tests of DFH sliders at 1 nm clearance were conducted to understand the minimum clearance for stable and reliable flying of DFH sliders. Multiple techniques were used to comprehensively evaluate the HDI stability and reliability at ultra-small spacing. Experimental results indicate that all of the sliders tested could fly stably at 1 nm DFH clearance without HMS modulation increase or contact. And little lube pick-up on the ABS was seen for all tested sliders. Also, the only lube depletion and disk carbon wear was TD-induced and not significant. Moreover, 1 nm flying did not cause severe slider DLC wear for this test. Light wear observed on some parts is independent of flying duration and may be TD related.

Consequently, the possibility of stable and reliable flying of the DFH slider at 1 nm clearance was demonstrated experimentally though the test results may be ABS/disk dependent, which indicated that a reliable HDI for 1 Tbit/in^2 or higher areal density may be possible using current DFH (or thermal fly-height control) technology. Furthermore, 1 nm clearance is probably not the limit for stable flying and further study is needed to understand the HDI performance at clearances below 1 nm.

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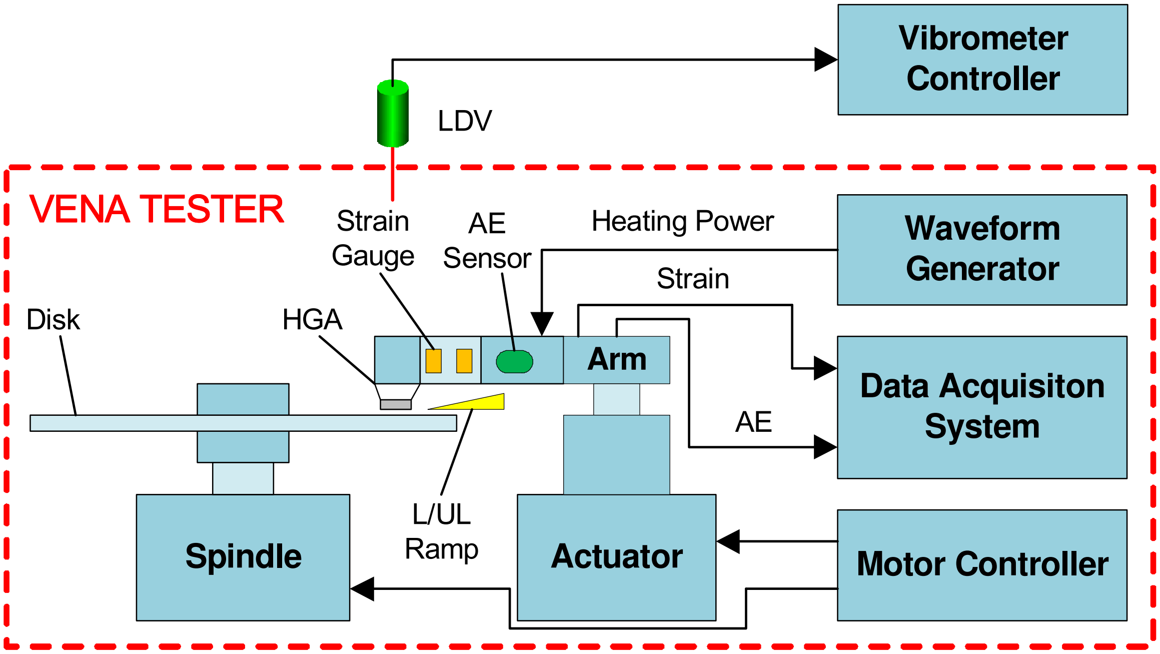


Fig. 1—Schematic of the experimental setup.

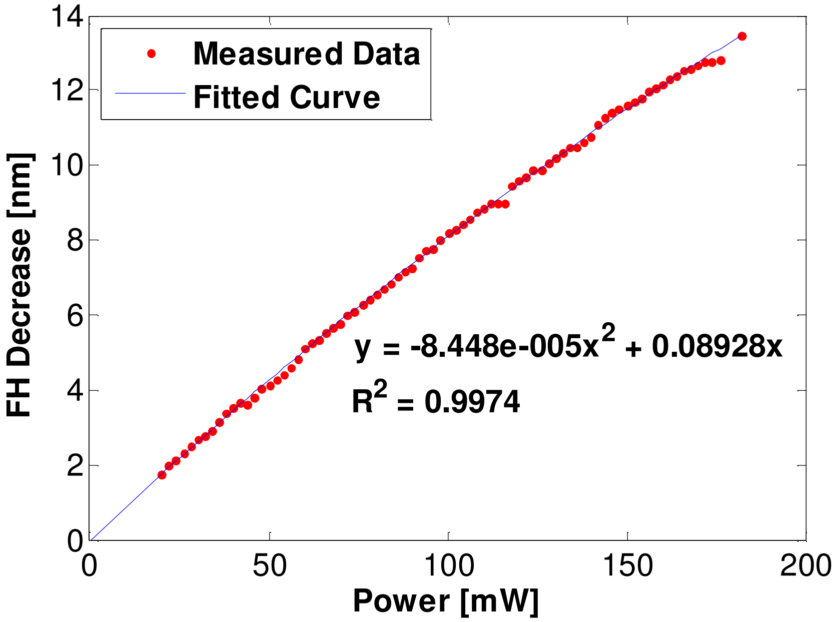


Fig. 2—Calibration curve of FH reduction vs heating power.

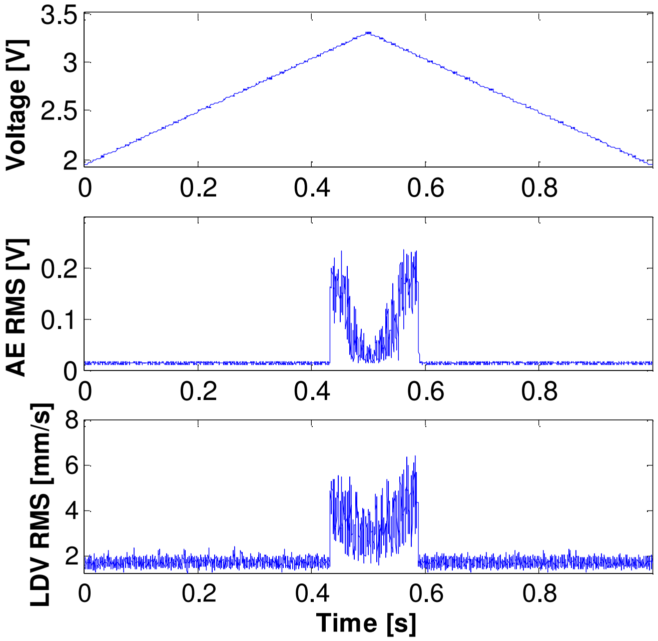


Fig. 3—Detection of thermal protrusion induced TD using AE and LDV signals as the heater voltage ramped up and down.

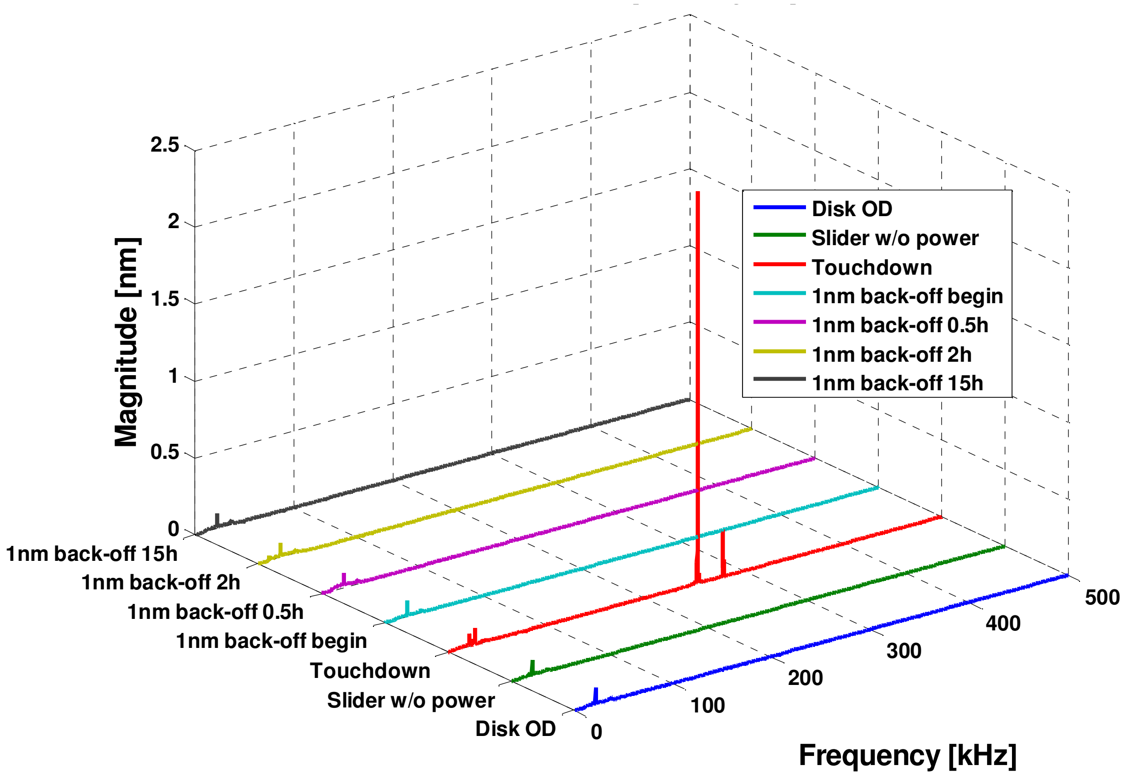
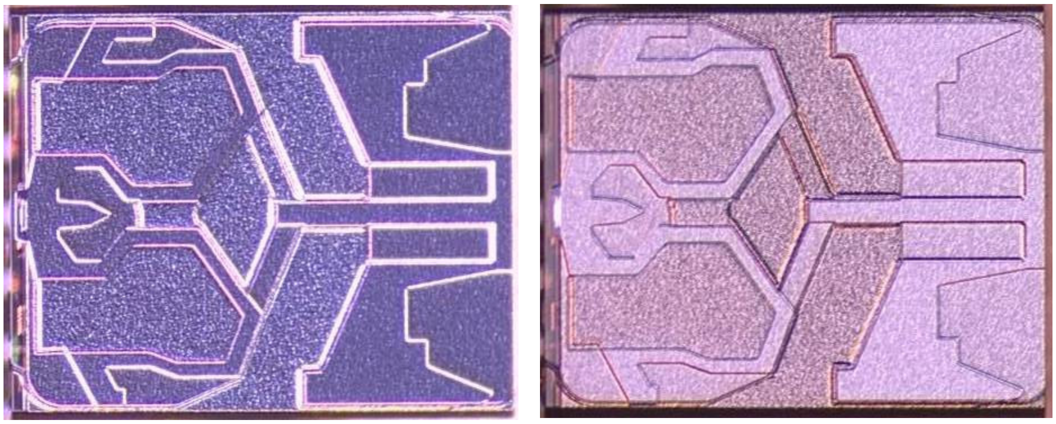
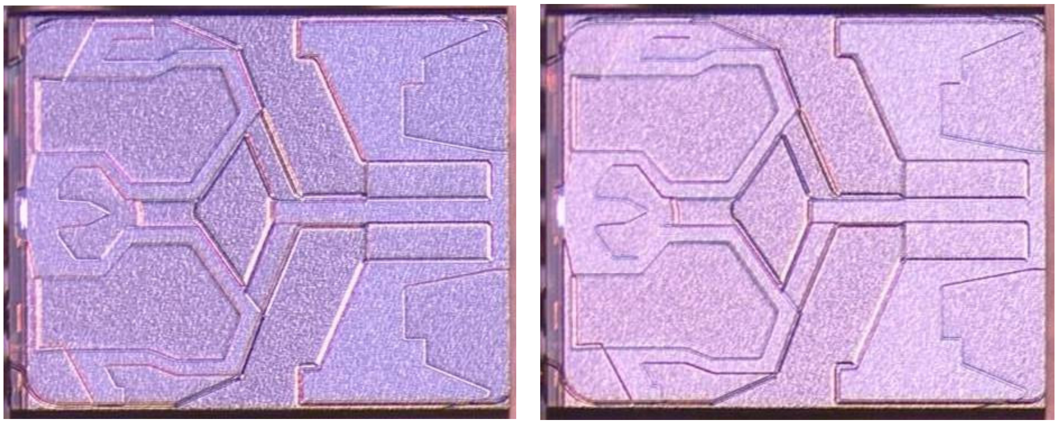


Fig. 4—Frequency spectra of the sliders and disk vertical vibration measured using LDV (10 kHz high-pass filtered).



(a) TD only **(b) 0.5 h**



(c) 2 h **(b) 15 h**

Fig. 5—Optical micrographs of the slider ABS after 1 nm clearance flying for 0 h (TD only), (b) 0.5 h, (c) 2 h and (d) 15 h.

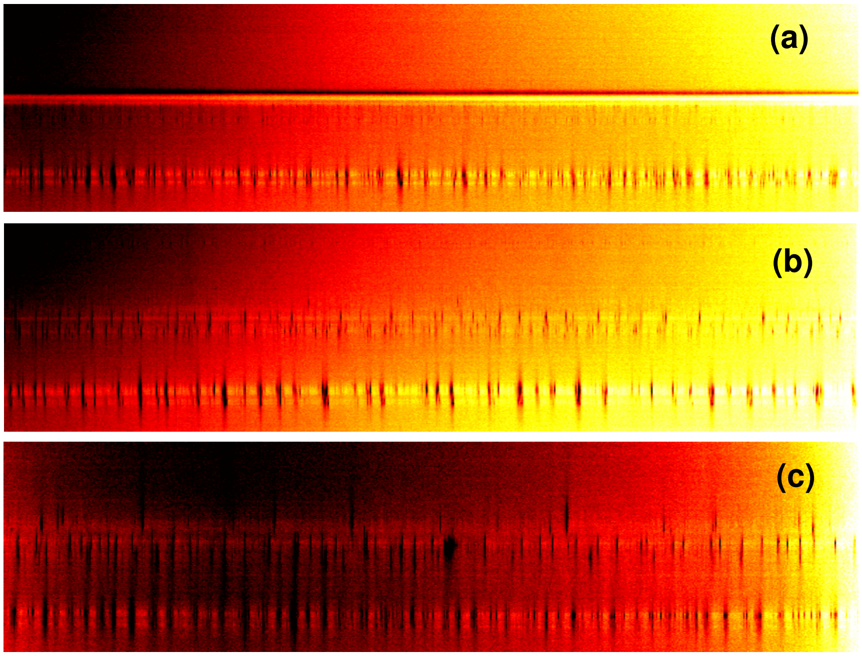


Fig. 6—OSA Q-phase images of lubricant film under the slider on disks after flying at 1 nm clearance for (a) 0 h (TD only), (b) 0.5 h and (c) 15 h. The dark contrast indicates lubricant accumulation and the bright contrast shows lubricant depletion.

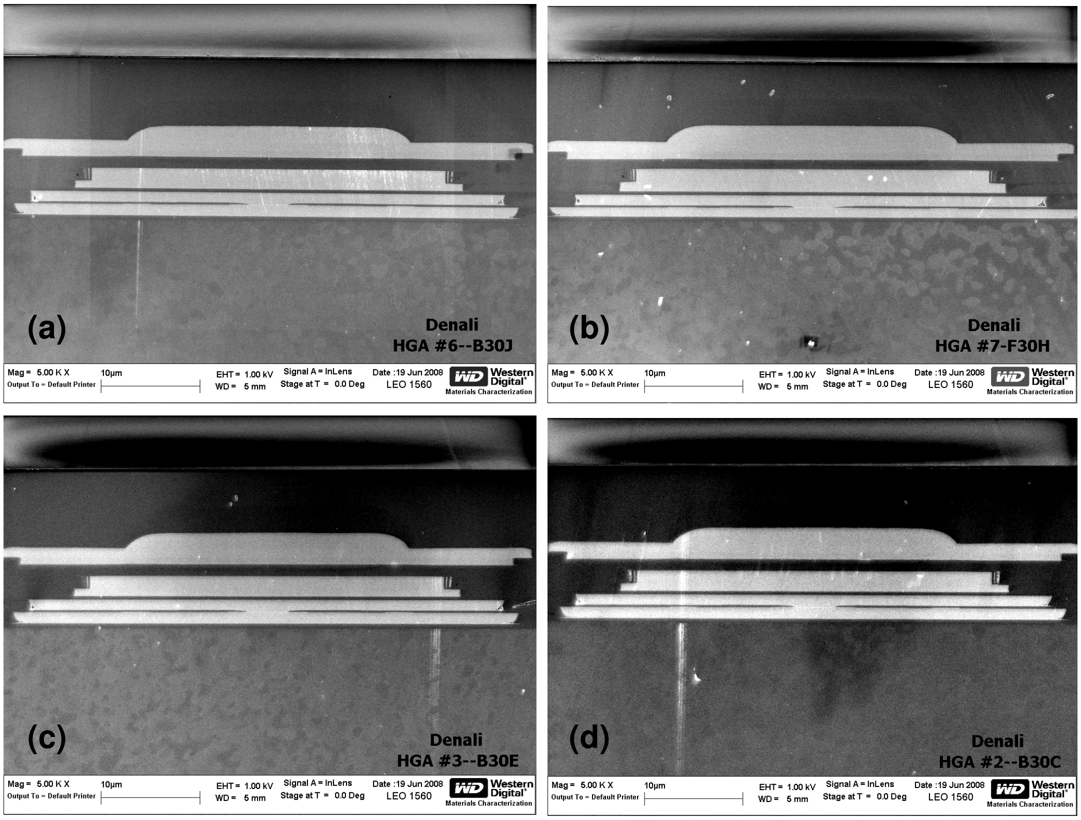


Fig. 7—SEM images of the read/write transducer region on the sliders after 1 nm clearance flying for (a) 0 h (TD only), (b) 0.5 h, (c) 2 h and (d) 15 h.

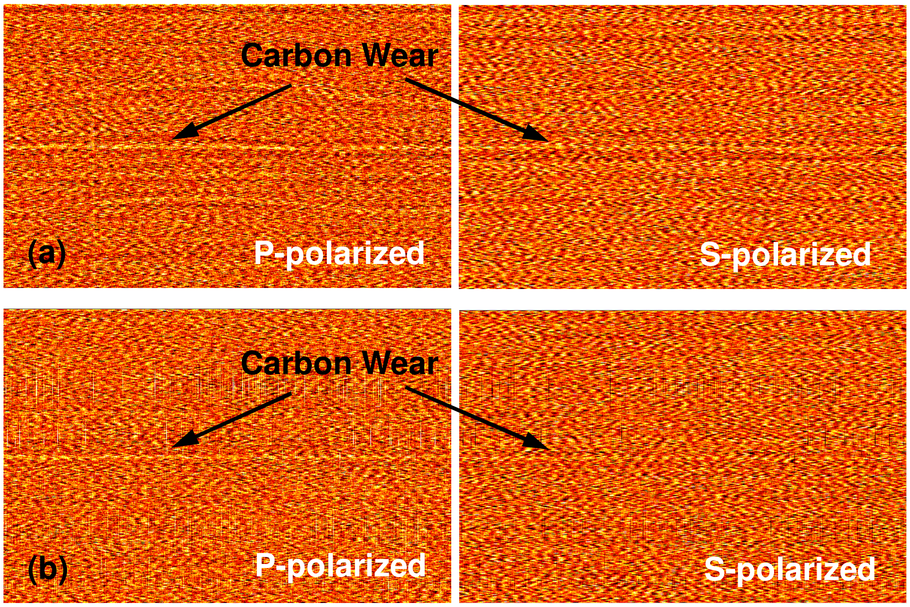


Fig. 8—P and S specular light images of the disks after (a) TD and (b) TD + 15 h of 1 nm clearance flying.