Roughness of Thin Perfluoropolyether Lubricant Films: Influence on Disk Drive Technology

C. Mathew Mate, Michael F. Toney, and K. Amanda Leach

***Abstract*—In disk drive technology, lubricant thickness and roughness are important, but often overlooked, contributors to slider–disk spacing. In this paper, we use X-ray reflectivity to measure the thickness and lubricant–air roughness of a perfluoropolyether lubricant (Fomblin Zdol) on silicon wafers and carbon overcoats. For Zdol on smooth silicon, the roughness increases with increasing lubricant thickness consistent with capillary wave roughening. For Zdol on the rougher surface of amorphous hydrogenated carbon, the lubricant smoothes to a value limited by the capillary wave roughening. We show that the lubricant density above the surface does not reach the density of air until approximately 3σ away from the average lubricant thickness. This lubricant–air interface width contributes substantially to current and future slider–disk spacings.**

***Index Terms*—Disk drives, lubrication, X-ray reflectivity.**

I. INTRODUCTION

IN DISK DRIVES, the density of magnetic bits on each disk surface has increased dramatically in recent years. This rapid increase in areal density has resulted in a concern that we may soon approach the physical limits of magnetic recording. For example, numerous researchers have studied how super-paramagnetism can limit the long term stability of closely packed magnetic bits [1]. In this paper, we consider, rather, limitations imposed by the lubricant at the head–disk interface. We show how the roughness of the lubricant films on disk and slider surfaces limits how closely a recording head can fly on an air bearing above the magnetic media. This roughness may limit the extendibility of current disk drive technologies.

The roughness of the lubricant films comes from thermally excited capillary waves that are physically intrinsic to all liquid–vapor interfaces. We have determined using X-ray reflectivity that, for Zdol lubricant films, 1 to 3 nm in thickness, on atomically smooth silicon surfaces, capillary waves induce a root-mean-square roughness σ of 0.2–0.35 nm. When Zdol is deposited onto sputtered hydrogenated carbon overcoats, the lubricant surface tension works to smooth out the rougher carbon surface, but the smoothness of the Zdol–air interface is limited by the thermally excited capillary waves. We also show that the lubricant density above the surface does not reach the density of air until approximately 3σ away from the average lubricant thickness. Consequently, both the average lubricant thickness on the disk and slider surfaces and the 3σs of their interface roughness must be included in the budget for the magnetic spacing between the recording head and disk media. This analysis indicates that the lubricant films at slider–disk interfaces are much larger contributors to the magnetic spacing than currently appreciated.

II. THEORY FOR CAPILLARY WAVES

Thermally excited capillary waves on liquid surfaces have a physical origin that bears a resemblance to that for superparamagnetism in the disk's magnetic media. In superparamagnetism, the probability that thermal agitation will cause a magnetic particle to switch its magnetization direction is proportional to $\exp(-KV/kT)$, where K is the anisotropy constant of the magnetic material, V is the particle volume, k is Boltzmann's constant, and T is the absolute temperature [1]. KV represents the work needed to switch an individual particle's magnetization direction.

For a liquid film with thickness h on a solid surface, the probability that thermal agitation will cause a displacement $z(x, y)$ in thickness at the location (x, y) away from the mean of the liquid–air interface is proportional to $\exp(-W(z)/kT)$, where $W(z)$ is the reversible work necessary at equilibrium to impose the disturbance. For ultra-thin liquid films, the work against gravity can be neglected (no gravity waves), and W consists both of the work against surface tension γ and against the free energy per unit area P that the liquid film experiences from the interactions with the underlying solid, such as van der Waals interactions:

$$W = \iint \left\{ \gamma \left[\left(1 + \frac{\partial z^2}{\partial x} + \frac{\partial z^2}{\partial y} \right)^{1/2} - 1 \right] + P(h+z) \right\} dx\,dy. \tag{1}$$

The air pressure, which might be induced by a slider flying over the surface, does not appear in (1) as $P_{\text{air}}\, dV_{\text{lubircant}} = 0$.

If the distorted surface is represented as a Fourier series, the first term in (1) can be linearized and distorted surface represented as decoupled harmonic waves—capillary waves—and the density profile as a function of z can be calculated [2]. If the liquid film is thinner than the dewetting thickness and is on a smooth solid surface, theories of the roughness of liquid–vapor interfaces give the standard deviation σ of the surface fluctuations normal to the surface as

$$\sigma = \sqrt{\sigma_0^2 + \frac{kT}{2\pi\gamma} \ln\left(\frac{\lambda_l}{\lambda_s}\right)} \tag{2}$$

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C. M. Mate and M. F. Toney are with the IBM Almaden Research Center, San Jose, CA 95120 USA (e-mail: {mate; toney}@almaden.ibm.com).

K. A. Leach is with the Polymer Science and Engineering Department, University of Massachusetts, Amherst, MA 01003 USA.

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where σ_0 is the molecular roughness and the second term represents the roughness from thermally excited capillary waves on the liquid surface [3]. λ_s and λ_l are, respectively, the shortest and longest wavelength of capillary waves that can be sustained at the liquid–vapor interface. λ_s is on the order of the distance between the atoms or molecules in the liquid (~1 nm), and λ_l is limited by the attractive interaction with the underlying substrate, the $P(h+z)$ term in (1). If this interaction comes mainly from van der Waals forces, then

$$\lambda_l = 2\pi h^2 \left(\frac{2\pi\gamma}{A}\right)^{1/2} \tag{3}$$

where A is the Hamaker constant [4]. For a 2 nm thick lubricant film, typical for today's disk drives, $\lambda_l = 31$ nm, using $A = 10^{-19}$ J [5] and $\gamma = 24$ mN/m. So, capillary waves on the surface of lubricant films in disk drives have very short wavelengths, ranging from 1 to 31 nm.

III. EXPERIMENTAL RESULTS

As most of the experimental details of our X-ray reflectivity results and sample preparation have been discussed in earlier papers [4], [6], we describe them only briefly: In specular X-ray reflectivity, the reflected X-ray intensity is measured as a function of incidence angle and analyzed using a multilayer model incorporating several parameters—thickness and density of the lubricant film and roughness of the lubricant–air and the substrate-lubricant interfaces—that are varied to produce the best fit to the data. From this modeling, the functional form that best fits the density profile of the lubricant–air interface is an error function, implying a Gaussian distribution of surface heights. Fomblin Zdol {HO–CH_2CF_2–$(OCF_2CF_2)_n$–$(OCF_2)_m$–OCF_2CH_2–OH with 4700 g/mol molecular weight} was dip coated onto either clean silicon wafers with 1.5 nm of native oxide or onto the surface hydrogenated carbon overcoats (12 nm thick, 35% H) sputter deposited onto silicon.

In Fig. 1 shows an example of the density profiles fitted to the X-ray reflectivity data for Zdol on a carbon overcoat. The Zdol profile exhibits a dip in density at the Zdol-carbon interface due to the adsorption of a hydrocarbon layer between the Zdol film and the carbon overcoat [6]. The Zdol–air interface is narrower than for the bare carbon surface, due to the surface tension trying to pull the liquid surface flat, but still has a finite width due to roughening by capillary waves.

In Fig. 2 we plot σ as a function of Zdol thickness on the silicon and carbon substrates as determined from the X-ray reflectivity results. The following trends are apparent:

1) The initially smooth sample–air interface of the silicon wafer becomes rougher with the addition of the Zdol.
2) The rougher sample–air interface of the carbon becomes progressively smoother with the addition of the Zdol and eventually converges to approximately 0.35 nm, the same σ value as the Zdol–air interface on silicon.
3) Both bonded and unbonded Zdol have the same polymer–air interfacial roughness.

The solid line in Fig. 2 shows the σ predicted from (2) and (3) using $T = 300$ K, $A = 10^{-19}$ J, $\gamma = 24$ mN/m, $\sigma_0 = 0.1$ nm, and $\lambda_s = 1.0$ nm. The agreement of the data with the solid line shows that the Zdol–air interface roughness on silicon wafers can be accounted for by thermally excited capillary waves in the Zdol, but only if a long wavelength cutoff determined by attractive van der Waals is used. That the bonded film has the same roughness indicates that the polymer–air interface can support thermally excited capillary waves even though the polymer ends are bonded to the silicon surface.

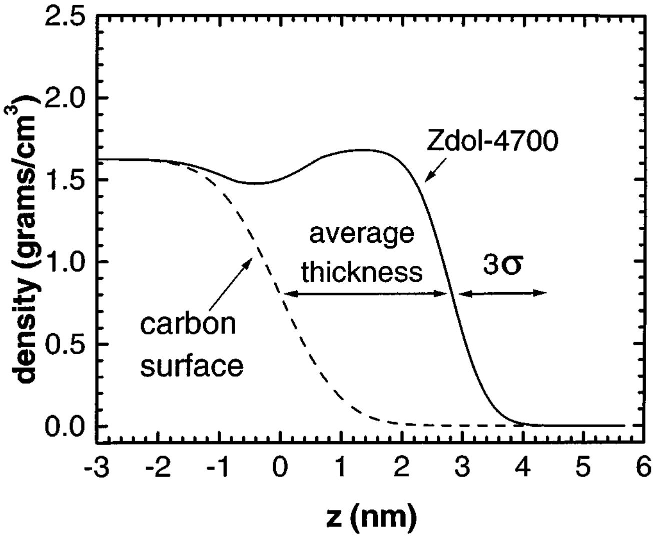

Fig. 1. Mass density profile that best fits the X-ray reflectivity data. The dashed line is for the initial carbon-air interface and solid line for after depositing a 2.8 nm thick Zdol film.

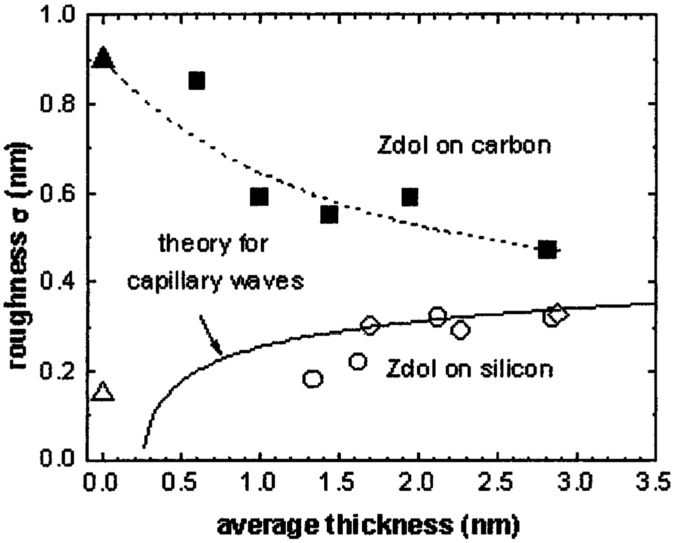

Fig. 2. Standard deviation σ of surface heights versus average Zdol thickness, both determined by X-ray reflectivity. Open symbols are for Zdol on silicon, closed symbols are for Zdol on carbon. Triangles are for unlubricated surfaces. The diamond is for Zdol thermally bonded (120 °C for 1 h) to the silicon surface. The solid line is the theory for roughening by capillary waves, while the dashed line is a guide for the carbon data.

IV. CAPILLARY WAVE LIMIT TO SLIDER–DISK SPACING

The right side of Fig. 3 shows schematically how the lubricant contributes to the slider–disk spacing when a slider with a recording head is flown near a disk surface. In today's drives,

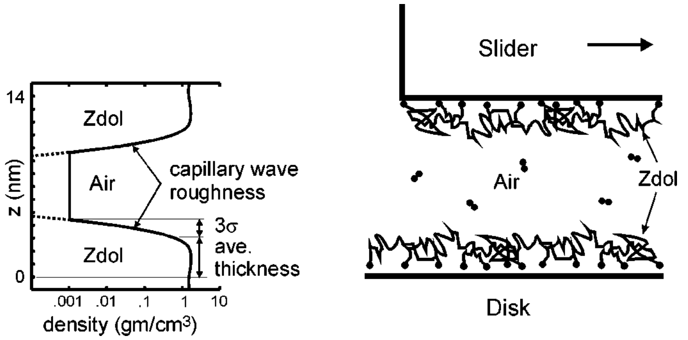

Fig. 3. Left: Density profile for lubricant films and air gap between a slider and disk surfaces with a 14 nm physical spacing. Right: Schematic representation of the lubricant and air at a slider disk interface.

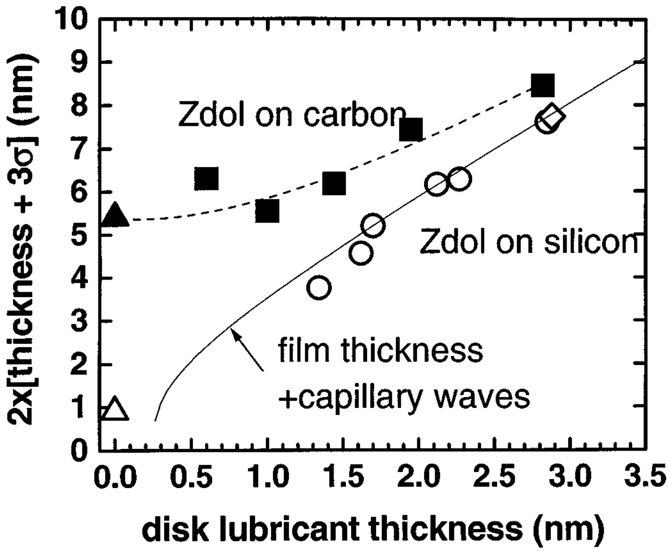

Fig. 4. Estimated contribution of lubricant to the slider–disk spacing.

disk surfaces are typically coated with 0.5 to 2 nm of lubricant. When a slider is flown close to the disk, it can pick up a similar thickness of lubricant from the disk [7], either through vapor transport across the small air gap or during the occasional contacts with the disk surface. The left side of Fig. 3 shows how the Zdol density should vary from disk to slider surface using the X-ray reflectivity result shown in Fig. 1 for the lubricant profile on both surfaces, but with density now plotted on a logarithmic-scale. Only at 3σ away from the surface mean does the Zdol density become equal to a typical air density in the air bearing gap. [For the error function density profile found by the X-ray reflectivity analysis, the density at $h + 3\sigma$ corresponds to the density of air at 2.3 atmospheres.] From Fig. 3, we see that, with a 14 nm physical spacing between the slider and disk surfaces and with 2.8 nm average thickness of lubricant initially deposited on the disk, only 5.5 nm is available for the air gap, with lubricant films and the lubricant–air interfaces taking up the remaining 8.5 nm of physical spacing.

We can estimate how the thickness of lubricant deposited on the disk will impact the slider–disk spacing by plotting $2(h + 3\sigma)$ versus the average lubricant thickness h on the disk. This analysis assumes that the slider picks up a lubricant thickness equal to that on the disk and that the slider roughness is the same as the disk roughness. This is shown in Fig. 4, where the points and lines come from the X-ray reflectivity data in Fig. 2 and from the theory for capillary waves, (2) and (3); therefore, the solid line represents the theoretical limit for the minimum lubricant contribution to physical spacing.

Data already exist in the literature to support a large lubricant contribution to the slider–disk spacing. First, when takeoff heights (the smallest possible fly height without contact) are measured as a function of disk roughness and are extrapolated to zero roughness, a positive intercept with the takeoff height axis is found, ranging from 2.8 nm [8] to 6.8 nm [9]. While this intercept has several contributors, our results indicate that several nanometers come from the roughness of the lubricant–air interfaces. Second, force-vs.-distance curves measured by atomic force microscopy show that, when a sharp tip is brought into contact with lubricant, the tip experiences a meniscus force at a distance 3 to 5 nm larger than expected from the film thickness [5], due to lubricant transfer to the tip and lubricant–air interface roughness.

If current trends continue, the areal density in disk drives is expected reach 100 Gbits/in^2 within the next five years, with a magnetic spacing of about 10 nm [10]. From Fig. 4, we see that 1 nm of disk lubricant would result in lubricant taking up a third of the 10 nm spacing budget, even if the slider and disk surfaces are perfectly smooth. This large contribution comes from the need to have two liquid–air interfaces, roughened by capillary waves, for an air gap to exist between the slider and disk. An obvious way to reduce the lubricant–air contribution to magnetic spacing would be to eliminate the need for an air gap between the slider and disk, resulting in contact recording.

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