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A hydrodynamic and kinematic analysis of chemical–mechanical planarization mechanism in double sided polisher

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ABSTRACT

In this study, a hydrodynamic and kinematic analysis of the double sided chemical–mechanical planarization (CMP) mechanism is discussed. The workpieces are disk substrates with a hole at the center. The hydrodynamic results show that the disk surface has a positive fluid pressure zone and a negative pressure zone. The positive pressure zone squeezes out the used slurry and the negative pressure zone sucks in the fresh slurry. The high pressurized slurry with abrasive particles has a significant interaction with the disk surface and removes the material. The self rotation of the disks inside the carriers is beneficial for the uniformity and global planarization of the disks. The kinematic analysis results show that a transient center of the carriers exists and the velocity magnitude and direction change abruptly at this position. It should be avoided on the disk surface, because such a transient center is a halt point which may cause defects on the disk surface. The velocity at the carrier center is steady, but the velocity at the carrier edge has a larger oscillation with a higher average number. The critical waviness and surface integrity can be optimized via the kinematic parameters by the abrasive particle trajectories on the disk surface.

1. Introduction

With the increment of the integration density and the reduction of feature sizes, chemical–mechanical planarization (CMP) has become an indispensable step in ultra large scale integration (ULSI) device manufacturing [1–3]. CMP has the capability to achieve sufficient local and global planarization and has been used in process architectures to form interlevel dielectric (ILD), shallow trench isolation (STI), damascene metallization and multilevel interconnects [4–7]. CMP has also been used to process various substrates, such as Si wafers, single crystal sapphires, Al–Mg alloy and glass substrates for hard disk drive (HDD), and glass touch panel substrates [8–10]. The process mainly involves the wafer and its holder, the polishing pad, the injected slurry and the applied load. Many parameters, such as environmental temperature, chemical reactions, pad/wafer interface, tribological behavior of the abrasive particles, and hydrodynamics of fluid, will affect the surface material removal [11–18]. The workpiece is planarized by abrasive particles, such as colloidal silica, alumina, silicon carbide, diamond and ceria, with the particle size from a few nanometers to submicron [19,20]. Balance between the chemical effect and the mechanical interaction is essential to achieve the desired thickness removal and uniform surface. The chemical impacts of surfactant [21], hydrogen peroxide (H_2O_2) [22], urea–hydrogen peroxide (urea–H_2O_2) [23], citric acid and alumina [24], complexing agent and inhibitor [25] in slurries have been widely discussed. However, the mechanical interactions, which are of extreme importance in CMP, have not been widely investigated. These interactions are especially critical to the global planarity, flatness, full surface waviness and roughness. Simulation modeling is a widely used method for the design of experiments (DOE), process development, failure analysis and troubleshooting, which significantly reduces the experimental workload and accelerates the process optimization [26–29]. It has also been used to explore the mechanical interactions of the CMP mechanisms in terms of hydrodynamics and kinematics [30–34].

The CMP process has essential tribological attributes, and the material remove rate (MRR) is generally represented by Preston's equation as [35,36]

$$MRR = C_p P V \tag{1}$$

where C_p is Preston's coefficient, P is the nominal pressure, and V is the relative linear velocity. The nominal pressure can be controlled by process setup. To define the relative linear velocity, kinematic analysis method is applied [37,38]. Many fundamental approaches have been endeavored to verify the linear relation of Preston's law using an elastic material model [39], an asperity contact model [40,41] and an erosion model [42]. However, it has been empirically observed that linear Preston's equation is not consistently valid, and some modified equations have been proposed with non-linear

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expression of pressure and velocity [5,43,44]. The primary factors of pressure and velocity in Preston's equation have been well explored for single sided polishers used for integrated circuits (IC) [17,44,45]. The hydrodynamics for the single sided wafers has been investigated and the 3D fluid pressure distribution has been simulated [46,47]. Double sided polishers have been widely applied for silicon wafers [48] and rigid magnetic disk substrates [49,50]. Compared with single sided polishing, the process mechanisms of the double sided polishing have remained to be less explored from the hydrodynamic and kinematic standpoints, especially for the workpieces with a hole at the center. For the double sided polishing, the relative motion is more complicated due to more process parameters such as top/bottom plate and ring/sun gear speeds. Comprehensive analysis is required to understand the CPM mechanism for the double sided polishing system. Thus, the purpose of this study is to provide a fundamental understanding of the hydrodynamics and kinematics of CMP mechanism of a double sided polisher for processing Al alloy HDD substrates.

As the advance of the areal density, the spacing of the magnetic head flying over the magnetic recording disk steadily decreases [51,52]. The head-media spacing (HMS) of the current perpendicular magnetic recording (PMR) product is approximately 10 nm, and the fly height is close to 5 nm [53,54]. The HMS and fly height can be even lower for pseudo-contact recording or heat-assisted magnetic recording [55–59]. With the magnetic head operating so close to the disk surface, the media surface must be ultra-smooth without defects, such as particles, nanoasperities, scratches, pits or other micro defects, to avoid head crashes [60] and reduce the thermal asperity or bit error rate (BER). CMP is critical to the quality of HDD substrates and it is a typical double sided polishing process. The results of this study will be beneficial for understanding the CMP mechanisms of the HDD substrates and optimizing the CMP process for various double sided polishing applications.

2. Modeling

2.1. Polishing machine setup

In this study, the CMP machine is a Speedfam 16B double sided polisher (SpeedFam Co., Ltd., Japan), which is widely used to precisely manufacture HDD substrates. The polishing machine consists mainly of the top and bottom plates as well as the sun and ring gears, whose rotation speeds and directions can be controlled separately by four motors. The surfaces of the top and bottom plates are covered with a porous soft polyurethane pad. The cogs of the carriers are engaged simultaneously with the sun gear by the outer circumference and the ring gear by the inner circumference. The rotation of the carriers is passively driven by the sun and ring gears and their speed and direction are dependent on the setup of the gears. The disks are situated inside the holes of the carriers and their motion is in company with the carriers. The disks are in contact with both the top and bottom pads under a certain compressive load during operation so that both sides of the disks can be polished. The carriers are thinner than the disks, so that the pressure is mainly loaded on the disks but not on the carriers. For 95 mm diameter disk product, each carrier can hold 10 disks, and every batch includes five carriers, thus 50 pieces can be polished simultaneously. The acidic slurry is supplied from the top through several 10 mm feed holes situated in the top plate. CMP is a chemical–mechanical process, and the chemical effect from the slurry will not be discussed in this study.

2.2. Hydrodynamic analysis

During the CMP process, the slurry flows in between the disk and the pad along with their relative movements. A wedge effect is produced and the disk with a radius of r_0 is tilted by a minute angle as shown in Fig. 1 [46,47,61]. The rolling angle (α) and pitch angle (β) are the attitude angles of the disk along the x- and y-axes, respectively, with respect to the pivot axis z. The system is in equilibrium of rotational moments around the pivot point. The attitude angles are influenced by the pressure distribution of the slurry between the disk and the polishing pad. A Reynolds equation was derived to obtain the pressure distribution for the incompressible slurry fluid from the Navier–Strokes equation [62]. The Navier–Stokes equations [63,64], named after Claude-Louis Navier and George Gabriel Stokes, describe the motion of fluid substances, and these equations are derived from Newton's second law for fluid motion, together with the assumption that the stress in the fluid is the sum of a diffusing viscous term, which is proportional to the gradient of velocity and pressure. A simplification of the Navier–Stokes equations for an incompressible Newtonian fluid with a constant viscosity is expressed as [65]

$$\rho\left(\frac{\partial v}{\partial t}+v\nabla v\right)=-\nabla p+\mu\nabla^2 v+f \tag{2}$$

where ρ is the fluid density, v is the flow velocity, p is the fluid pressure, μ is the dynamic viscosity constant, and f is other body forces acting on the fluid. This equation is a statement of the conservation of momentum in a fluid for a continuum.

By assuming: the fluid is Newtonian; fluid viscous forces dominate over fluid inertia forces; other fluid body forces (f) are negligible; the variation of pressure across the fluid film is negligible, i.e. $\partial p/\partial z=0$; the fluid film thickness is much less than the width and length and thus curvature effects are negligible, the Reynolds equation can be derived from Eq. (2) and expressed as [63,64]

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y}\right)=\frac{\partial}{\partial x}\left(\frac{\rho h(u_a+u_b)}{2}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h(v_a+v_b)}{2}\right)$$
$$+\rho(w_a-w_b)-\rho u_a\frac{\partial h}{\partial x}-\rho v_a\frac{\partial h}{\partial y}+h\frac{\partial \rho}{\partial t} \tag{3}$$

where x and y are the bearing width and length coordinates; z is the fluid film thickness coordinate; h is the fluid film thickness; u, v, w are the bounding body velocities in x, y, z directions respectively; and subscripts a and b denote the top and bottom bounding bodies respectively. As shown in Fig. 1, point C is an arbitrary point on the

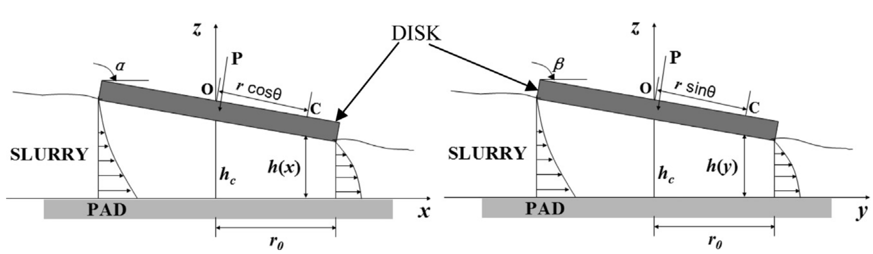

Fig. 1. Schematic of CMP lubrication model for slurry flow and film thickness [46,47,61].