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Tribology International 38 (2005) 235–242

TRIBOLOGY INTERNATIONAL

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Chemical boundary lubrication in chemical–mechanical planarization

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Abstract

Chemical–mechanical planarization (CMP) is a synergistic tribological process. It occurs between a polymeric polishing pad, a solid body to be made smooth, between which is a chemical slurry containing nanoparticles of abrasive materials. CMP functions similar to chemical boundary lubrication of mechanical systems, except that the objective of the CMP is to remove materials in a controlled manner. In this article, the lubricating behaviors of CMP are reviewed.

Keywords: Chemical–mechanical planarization

1. Introduction

Chemical–mechanical polishing (CMP) was invented in the early 1980s at IBM and has since become a standard planarization process for making integrated circuits (IC) [1–4]. The objective of a CMP process is to obtain an atomically smooth surface across a rigid flat (wafer). The standard flat has a diameter of 300 mm (12″). Fig. 1 is the schematic of a CMP process. It contains a rotating (disk) holder with a flat (wafer) facing down, a slurry dripping system, and a rotating soft-pad desk. The flat substrate is mostly silicon. On top of the flat there are several layers of a variety of materials. Metal layers are coated using chemical vapor deposition (CVD), physical vapor deposition (PVD), or other methods. A subsequent step is to planarize the top layer so that another metal layer is deposited on this layer. A polishing pad is mainly polyurethane material embossed or grooved with different textures. Fig. 2 shows the scanning electron microscope (SEM) micrograph of a pad surface. The bottom portion in this figure is the original pad surface and the top shows a pad with the surface layer removed. The removal of the pad surface layer was possible using a diamond abrasive disk. This process is called conditioning—a standard step of a CMP process. The objective of the conditioning process is to roughen the pad surface as well as to remove a surface layer with chemical residual. A polishing slurry is composed of nanoabrasive particles, oxidizer, and surfactant in deionized water.

Depending on the development of microelectronic packaging process, materials polished are in two categories: metals and non-metals. Metals include W, Al, Cu, and potentially Ta. Non-metals are Si, SiO_2, PETOS (plasma enhanced tetraethyl ortho silicate), Boron Phospho Silicate Glass, and recently low K (dielectric constant) materials [5,6]. For metal polishing, it is widely accepted that a complete passivation, rather, oxidation film is formed and subsequently removed [7]. Other report, however, indicated that slurry viscosity [8] and electrochemical interaction [9] played important roles in materials removal. For silicon-based non-metals polishing, evidence shows the formation of silica triggered by friction forces [10–13]. The lubrication behavior of a CMP process is still an art to many. Although hydrodynamic lubrication regime has been mentioned, the physical contact between a polishing polymeric soft-pad and a solid flat during CMP have been proven [14–18]. Further studies proved that there is no hydrodynamic lubrication during CMP [19–22]. In this review, attempts are made to discuss tribological performance of CMP processes. In the following, a brief review of the chemical, mechanical, and rheological aspects of CMP appears first, followed by discussions of examples of evidence. The final analysis leads to the conclusion that CMP is a chemical boundary lubrication (CBL) process. This means that during CMP, the boundary lubrication results from chemical reactions between constituents in liquid lubricants

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0301-679X/$ - see front matter
doi:10.1016/j.triboint.2004.08.006

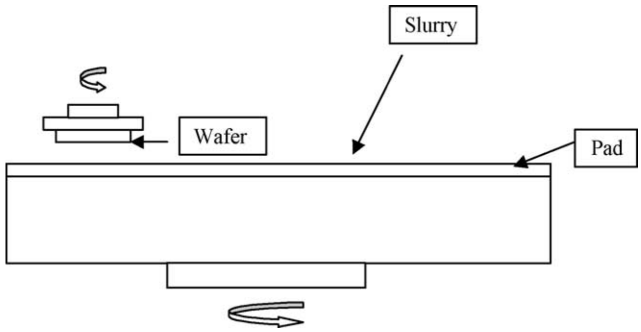

Fig. 1. Schematic illustration of a CMP system.

and solid sliding surfaces. The CBL is distinct from the conventional boundary lubrication where there is no chemical reaction involved.

2. Lubrication behavior of CMP

The lubrication qualities of CMP slurries has been studied in last few years [8,14,19,21]. The first step evaluating the lubrication of a CMP process is to establish a 'Stribeck' curve, i.e. the average friction coefficient as a function of relative surface speed and applied load were measured for polishing performance. Two examples are shown in Fig. 3, where Si and Cu CMP were polished, respectively. The friction force was measured using a load sensor attached to the flat holder. Underneath is the polishing pad. The viscosity of the slurry (water) with velocity and load, into one group variable were combined to estimate the classical Stribeck curve [21–24]. Similar to the Stribeck curve, the grouping can be described as $Sc = \eta U/W$. Here, Sc was measured for comparison purposes only, where η was viscosity of slurry—assuming as 1 Ns/m^2 (10^{-3} Pa s) for water-based slurries, U was relative speed of flat and pad in mm/s, and W was normal force in gram. Fig. 3(a) shows that the friction coefficient decreases with increasing speed. In the Cu CMP as shown in Fig. 3(b), the addition of hydrogen peroxide and 0.3 μm abrasive particles increased the friction coefficient steadily. Fig. 3(c) shows also the change of friction when different slurries were added. This result showed that the increased friction coefficient is mainly due to the addition of abrasive particles. When acidic and alkaline alumina slurries are used, the friction also changes, as shown in Fig. 3(c). It is reminded that the purpose of a CMP is to remove surface materials to achieve a supper smooth surface across the solid surface. The relative surface speed of a flat changes from its center to edge. Therefore, the measured friction coefficient is only an average of the flat against the pad. In Fig. 3, Si CMP in water has lower friction than that of Cu CMP. This means that the Si surface is lubricated with the hydration of Si. The effect of changing surface chemistry on friction coefficient is also seen in Fig. 3. The friction coefficient is affected by the addition of H_2O_2 and abrasive particles as well as the changing pH and polishing conditions (load and speed).

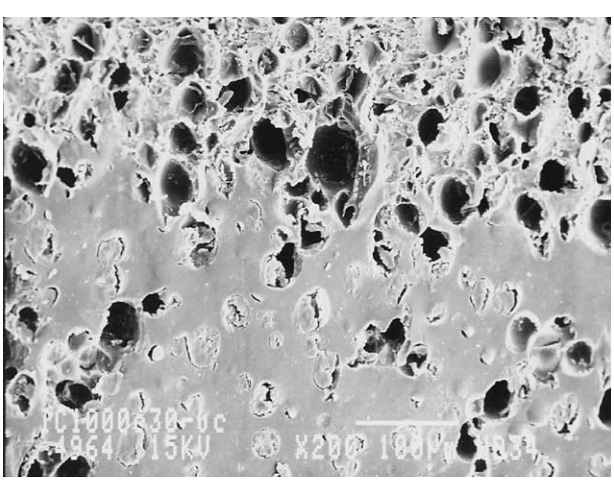

Fig. 2. SEM micrograph of a polyurethane polishing pad surface. Top portion: conditioned. Bottom portion: as received.

In an industrial CMP process, the friction is kept constant. A diamond conditioner used to roughen the pad surface helps to maintain the polishing stability. In this aspect, the 'Stribeck curve' in CMP has no means in being similar to a journal bearing where the Stribeck curve was originally developed.

3. Materials removal mechanisms during CMP

Chemistry plays an important role in CMP. In the following paragraphs, the effects of electrochemical reactions along with physical and mechanical processes are discussed.

3.1. Chemical wear in metal CMP

Metals commonly used in today's integrated circuits (IC) manufacturing include tungsten, aluminum, copper, and tantalum. The tungsten and copper are widely used metals in integrated circuits manufacturing. In metal CMP, two competing mechanisms have been reported. The oxidation of tungsten was first proposed by Kaufman in 1991 [7]. Fig. 4 illustrates his model showing the oxidation and removal procedures. This model involves the formation of a blanket passivating layer on the surface of the tungsten due to the oxidizing nature of the slurry. According to this model, mechanical abrasion from the slurry, and the roughened polishing pad subsequently removes the passivating layer. The bare metal, when exposed to the oxidizer, immediately repassivates. The abrasion–repassivation process is hypothesized to continue until a layer that has a much lower polish rate than tungsten is formed. The polish contained potassium ferricyanide (an oxidant) about 3%, ethylenediamine (a complexant for tungsten),