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Chemical Mechanical Planarization

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Abstract

As feature size continues to decrease in microelectronics and integrated circuits, there is a greater need for global surface flatness of the various layers that make up these devices. CMP is the process used the most to achieve good results when planar surfaces are required. However, to improve the performance and efficiency of this process, there is a need for better understanding of the physics, chemistry and mechanical phenomena at the point of contact between the constituents involved in the polishing process. This study lists several models that attempt to predict CMP performance and comments on their features. A good model of CMP would have to be complex, and since most current models make numerous improbable assumptions, the results they predict do not closely match results obtained from experimental tests. The conclusion is that there is still need for better understanding of CMP in order to improve the process.

1. Introduction

Chemical Mechanical Planarization or Polishing is a material removal process used to remove manufacturing or machining imperfections. It is often used to make a surface as planar or uniform as possible for aesthetic or performance reasons. One area where CMP is currently used is the semiconductor industry. Integrated circuits are constantly experiencing improvements in their performance/size ratio and CMP is a process which limits these improvements.

While the name CMP is fairly new, the process itself has been in use for a long time. Glass polishing is a similar process with the same goals except that it has different materials involved.

However, even though this technique has been around for a long time, a good understanding of the basic underlying mechanisms is still missing. This is proven by the fact that models proposed by the literature have not been confirmed by prediction capabilities or satisfactory mechanisms studies. Therefore, most knowledge in this field is from empirical data.

2. CMP Fundamentals

2.1 Background

CMP was initially used to fabricate high performance metal structures made up of multiple layers. It is necessary because if each layer is as flat as possible, the imperfections created by the topography of previous layers are minimized and therefore the number of layers in the structure and its performance are maximized.

IBM is credited with the initial development of CMP for the semiconductor industry. They used it in fabricating silicon wafers and had experimental expertise in machines, pads and slurries. Most of the scientific understanding was derived on that of glass polishing which is not itself a quantitative theory.

The main equation that has been generally accepted as governing the CMP process is called Preston's Law:

$$RR = K_p * P * V$$

where

RR – removal rate of material

K_p – a constant, Preston's coefficient

P – local pressure on wafer surface

V – relative velocity of the point on the surface of wafer vs. the pad.

This equation states that the rate at which material can be removed is directly proportional to the pressure applied to the wafer and the relative velocity between the wafer and the pad. Preston's coefficient has to be determined experimentally and differs for different parameters such as pad material, slurry components or temperature. This equation provides a good approximation to the data obtained in practice, especially for silicon dioxide CMP.

2.2 Bearing problem

The bearing problem is applied to CMP because the slurry behaves as a lubricant. The slurry, even though it might contain small particle and highly reactive chemicals, is a fluid with low Reynolds number flowing in a gap with small clearance to length ratio. Therefore the pressure generation between the wafer and the pad cannot be ignored and it has significant effect on contact between the pad and the wafer.

To model the pressure distribution, a 2-D averaged Reynolds equation has to be used. This equation predicts the pressure if the speed, clearance and fluid properties are known. If the slurry is considered incompressible, this equation takes the form

$$d/dx(h^3 dp/dx)+d/dy(h^3 dp/dy) =$$
$$6\mu d/dx[h(u_a+u_b)]+ 6\mu d/dy[h(v_a+v_b)]-u_a dh/dx-v_a dh/dy+w_a-w_b$$

This equation is complex and most available models either solve the one dimensional version or use a finite element method to solve it. The height of the slurry film is difficult to predict since the pad is somewhat soft and it could deform so that it is no longer a plane. Also another source of confusion comes in when the height has to be defined. Some models define it as the distance between the wafer and the asperities while others define it as the distance between the plane of the wafer and a horizontal plane at the average height value of the pad.

2.3 Contact problem

Contact between the pad and the wafer occurs at two different scales- a global scale where the wafer carrier indents the pad as a punch indents an elastic half-space and a local scale where individual asperities contact the wafer due to load being higher then the fluid pressure can support.

Contact pressure distribution for indentation by a rigid, flat-ended punch is given by the equation

$$p(x) = P/[a\pi(1-(x/a)^2)^{1/2}]$$

This formula is for a two dimensional infinitely long punch and the wafer is a three dimensional circular contact problem. However it is worth noticing that this formula predicts infinite pressure at the ends of the punch and experimental data shows very high wear at the edge of the wafer after CMP.

Unfortunately most models do not incorporate a global contact pressure prediction. The only contact taken into account is the statistical based Greenwood and Williamson model to describe the contact of a rough surface with a smooth plane. According to this theory, the nominal load and area of contact are a function of the distance between the flat surface and the average of the rough surface and are given by the equations

$$P_{nominal} = 4/3E^{*}R^{1/2}N\int_d^{\infty} p(z)(z-d)^{3/2}dz$$
$$A_{contact} = \pi RN\int_d^{\infty} p(z)(z-d)dz$$

This translates into a constant mean pressure of contact. These equations have been derived after several assumptions have been made, however. One assumption is that all the asperities in the pad are shaped as spheres and the contact creates elastic deformations only. Another assumption is that the wafer starts the polishing process completely flat. If this last assumption was true, the purpose of CMP would be defeated.

Another contact component comes from the particles in the slurry. These are usually abrasive particles (usually nano sized) and they remove material either by sliding or rolling across the surface or the wafer. However research in this field is still state-of-the-art and very little is known about what parameters affect removal rates.

2.4 Diffusion problem

The last important mechanism of CMP is a chemical effect. The slurry used in CMP is selected so it reacts with the wafer being polished. This oxidizes or etches the surface changing its mechanical properties and facilitating material removal. The governing equation for the mass transfer of the chemical from the slurry into the surface of the wafer would be the diffusion equation listed below.

$$dC/dt = c\ d^2C/dz^2$$

In this equation C would be the concentration of the chemical and would be different for different locations on the wafer. The mass diffusion constant has to be measured experimentally and is a function of slurry components and wafer material. Ideally concentration C would be the same for all locations in the wafer-pad interface in order to achieve uniform etching and mechanical properties of the wafer. However, uniform C is hard to achieve with a limited slurry flow. Therefore, due to this effect, material removal will be higher upstream than downstream in the slurry flow field.

3 Current issues in CMP
3.1 Recent state-of-the-art advances

Several recent studies have concentrated on these several different aspects of CMP. Some are just experimental tests to try to further match the known governing equations to actual data. There are also several models and simulations that have been build using one or more of the above theories in order to predict the end result of CMP.

One of the areas discussed in the literature is the actual pressure distribution on the surface of the wafer. Guanghui develops a relationship between the wafer surface pressure and wafer backside loading. This is an analytical solution to the contact between a plate and a elastic half-space. His model shows that under uniform pressure on the wafer backside, there still will be edge effect due to the pressure variation at wafer-pad interface. Sorooshian develops a relationship between the pattern density of the wafer and the effective pressure for an applied wafer pressure. This problem is similar to the Greenwood and Williamson contact problem. If the number of asperities is changed, the probability density function of the peaks changes and the mean pressure changes.

Material removal rate is also a function of polishing pad topography. Changxue considered material removal associated with a single asperity. This allows for a clearer identification of statistical issues. It also allows incorporation of more realistic assumptions concerning the pad such as asperities with random tip radii and asperities that have been blunted in the CMP process. He also discovered that initial asperity height pdf can have a significant effect on predicted MRR. Castillo-Mejia also found that the mechanical behavior of the asperity layer deviates significantly from that expected based on the properties of the individual asperities or the properties of the bulk of the pad.

Another determinant of MRR in CMP is the slurry and the particles it contains. Wonseop finds that friction force between the wafer and the pad is a function of down load, particle size and particle loading. An increase in down load or particle loading leads to an increase in number of particles in contact, much like the number of asperities in the GW theory. This study also finds that for constant particle loading, a decrease in size of particles results in increase in total contact area of particles and results in higher friction force. It also confidently states that results are in agreement with physical observations, despite the fact that it contradicts itself. Tamboli's study on particles compares obtained experimental data against four established models for CMP. None of the models could match the data satisfactorily.

There are currently several models that simulate CMP. Thagella models tribological issues and removal rate and finds experimental results well correlated with the predicted values of the model. The model is not described in detail as it is borrowed from one of the references. Kuide proposes a model incorporating both the chemical and mechanical effects. The hydrodynamic pressure of the lubricant is considered negligible, the chemical effects are included in a surface layer thickness on the wafer and a GW method is considered for mechanical contact. Particles and the removal rate per particle is calculated by comparing the surface layer thickness to the penetration depth. However the number of particles in contact is assumed to be the density of particles times the volume extruded by the real area of contact and the diameter of the particles. The conclusion states that "the present model appears to be capable of explaining many experimental observations".

Saxena's model also incorporates chemical and mechanical effects and ignores slurry pressure but takes a different approach. It assumes the pad to be a soft planar surface and the wafer to have imperfections. The pad is deflected by the wafer surface and the pressure is calculated by the one dimensional elastic half space relation. The material removal model is based on surface kinetics on the wafer feature surface. This model claims results consistent with experiments and also with results reported in the literature.

One last model is proposed by Xiaoquing. This model does not take into account the chemical effects of CMP. The mechanical deformation is governed by the Winkler foundation model (similar to a punch in an elastic half space). The model also incorporates the Reynolds equation for slurry pressure. The results reproduce a domination of the fluid pressure observed in experiments. This model doesn't incorporate any material removal mechanisms but it notes that hydrodynamic pressure deforms the pad and changes the lubrication boundary. A analysis by Seok on elastic layers coupled to viscous fluids also finds pad deformation when pressure is present.

3.2 Problems with process

The main problem in CMP is poor control over the process variables with narrow process latitude. For example, it is hard to design machinery with uniform etchant concentration under the wafer. Another problem are defects from CMP that affect die yield such as dishing, erosion, and edge effect. So a perfect flat surface is not obtained even after the CMP process. Therefore, CMP requires process development for process control and metrology. Also another drawback is the cost of CMP. Machinery is expensive to operate due to high equipment and consumables costs. Pads, slurry and machine parts have low life numbers and cannot be reused. CMP is not currently a very efficient process.

4. Alternate procedures

There are several alternative techniques to CMP. Spin on deposition (SOD) is a technique where different glasses are applied to the surface of the wafer in order to fill in gaps and planarize it. It is called the spin on technique because the wafer is spinning when the glass is applied so the centrifugal force spreads the liquid glass evenly. Etch back is an extra step that can be added to the SOD process in order to further reduce surface topography. While the SOD fills in gaps and trenches, the EB process tends to remove peaks and high regions on the wafer using chemical interaction.

This etch back process has led to a completely new process called spin etch planarization (SEP). In this process the wafer is held on a spinning chuck by a nitrogen cushion. As the wafer is spun, etch solutions are dispensed on the wafer. A planar surface is achieved by using the right solutions. Also because there is no external contact, there is no possibility of defects such as scratches. Also dielectric dishing, erosion and non-uniformities are kept very low.

However, CMP is still the leading process used for polishing of semiconductor devices. It offers excellent local and global planarity on the surface of the wafer. The SOD process only offers good local planarity even when combined with EB. Also the glasses applied have limited ability of filling in the gaps especially under 300 nm range. The SEP process is fairly new and it is more costly than CMP. It is also limited to the materials it can be applied to and it is not applicable to multimaterial surfaces. Also, unlike all other processes, CMP doesn't rely on any hazardous gases common in etching processes.

5. Conclusions

CMP is a complex problem not very well understood. There are few governing equations all derived from experimental data. More precise/accurate equations derived analytically are needed for a better controlled CMP process with better outputs. Most existing models are incomplete and do not illustrate data obtained experimentally. Other alternate processes are not as effective as CMP as they are neither cost-effective nor good at providing a global planar surface.

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