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Theoretical model and experimental analysis of chemical mechanical polishing with the effect of slurry for abrasive removal depth and surface morphology of silicon wafer

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ABSTRACT

This study considers the effect of the chemical reaction of slurry for chemical mechanical polishing and combines an analytical model of polishing times and the theory of specific downward force energy to construct a theoretical model to calculate abrasive removal depth of a silicon wafer that is polished by a cross-groove pattern polishing pad. Specific down force energy is used to calculate the thickness of the chemical reaction layer of the silicon wafer. A comparison of the average abrasive removal depths and the surface morphology of silicon wafer that uses simulation and experiment shows that the simulation results for the average abrasive removal depths and the surface morphology of silicon wafer are acceptable.

1. Introduction

Silicon wafer is a material used in semiconductor industry. The chemical mechanical polishing machine usually was used in the planarization process of silicon wafer. The average abrasive removal depth, removal volume and the condition of silicon wafer surface usually were investigated for the experiments of CMP. Besides, slurry was added in the CMP experiment, because it could make the silicon material softer. The pattern of polishing pad for CMP used in polishing silicon wafer would affect the condition of silicon wafer surface.

In 1927, Preston [1] presented the first CMP abrasion theoretical model, which is expressed as MRR = KPV, where MRR is the material removal rate, P is the pressure used, V is the relative speed of the wafer to the polishing pad and K is the Preston constant. This shows that material removal rate is related to the pressure used and the load. In 1990, Cook [2] further proposed the contact condition between abrasive particles and wafer surface and replaced the pressure and speed in Preston's equation with the positive stress and shear stress of the contact surface between the abrasive particles and the wafer. Cook also determined the effect of wear that is produced by contact between the abrasive particles and the wafer surface and by the chemical reaction. This describes the CMP model for the polishing process for silicon dioxide on a wafer surface.

Using contact mechanics, Chekina and Keer [3] analyzed the relationship between wafer surface morphology and contact pressure in the CMP wearing process under steady conditions and determined that the effect of planarization is related to geometric unevenness in a surface and different surface materials.

Jiang et al. [4] used a two-body abrasive model under multiple contact conditions and defined the wear energy of a material. A Gaussian distribution was used to assume the tip height distribution on the abrasive paper. Lin [5] proposed an analytical model for the material removal rate during specimen polishing. His model used micro-contact elastic mechanics, micro-contact elastic-plastic mechanics and abrasive wear theory. The equation for material removal rate from the specimen surface was determined to be a function of the average diameter of the slurry particles, the pressure, the specimen/pad sliding velocity, the Equivalent Young's modulus, the *root mean square* (RMS) roughness of the pad and the volumetric concentration of the slurry particles. Jongwon [6] developed a contact deformation effect model for abrasive particles and derived a volumetric removal model for individual abrasive particles. Lin and Chen [7] developed a method to calculate polishing times for chemical mechanical polishing that uses binary image pixel division.

Lin and Huang [8] observed the change in the amount of wafer substrate that is removed when a pattern-free polishing pad and a hole-pattern polishing pad are used with different downward forces, rotation speeds, abrasive particle sizes and slurry volumetric concentrations. In accordance with regression analysis theory, a compensation

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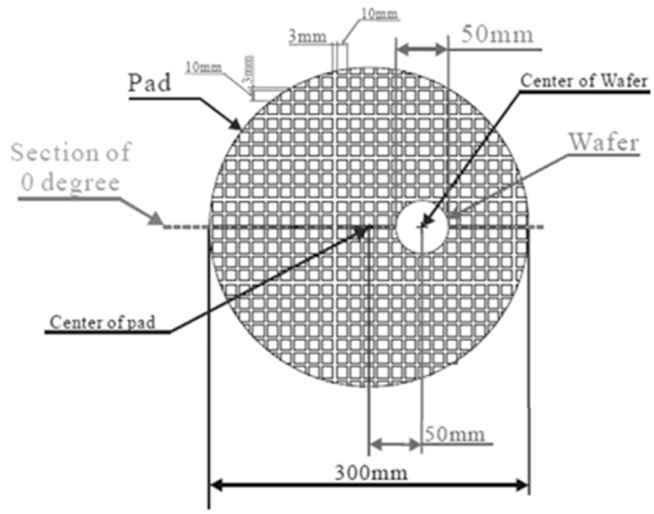

Fig. 1. The configuration of the cross-groove pattern polishing pad and the wafer for conventional CMP.

parameter, C_{rv}, was developed take account of the error that is caused by a change in the volumetric concentration of the slurry.

Lin and Wang [9] presented a theoretical model for abrasive removal depth for the polishing of a sapphire wafer using chemical mechanical polishing and a polishing pad that has a cross pattern. This model uses binary image pixel division to calculate the pixel polishing times and an abrasive contact model for a single pixel and multiple abrasive particles to estimate the contact force between single abrasive particle and wafer. When the contact force is calculated, Hertz contact force theory is used to calculate the abrasive depth of a single abrasive particle on the surface of the silicon wafer. This model supposes that the contact area between the surface of the cross pattern polishing pad and the wafer is flat and does not consider the contact area between surface of a cross pattern polishing pad and a wafer that has a Gaussian distribution. It also does not use the specific downward force energy theoretical equation to calculate the abrasive removal depth for a single abrasive particle on the surface of the wafer.

Wang et al. [10] optimized the chemical parameter in CMP process, but having minimized use of chemicals based on Box-Behnken design theory. Then, the disposal issue of toxic chemicals in chemical mechanical planarization could be avoided. Their study found that the material removal rate (MRR) was sensitive to pH value, more sensitive to slurry flow rate, and most sensitive to oxidizer concentration. Finally, they obtained the values of the optimal conditions for the abovementioned parameters.

Wei et al. [11] developed a mathematical model of material removal rate (MRR) to investigate the chemical action during chemical mechanical polishing (CMP) of ultra-thin SUS304 substrate (thickness<0.1 mm) based on the theoretical analysis and the experiments. They found that the mass of SUS304 substrate increased first, and then decreased later on. The material removal rate was proportional to the flow rate of the self-made acidic polishing slurry.

Gupta [12] et al. investigated the effect of pH on the removal rate (RR) of germanium (Ge) by chemical mechanical planarization (CMP) using polymorphs of titania. They used the rutile and anatase polymorphs of titania to study the removal rate of germanium in the absence of oxidizer. Polishing experiments using rutile titania showed that the highest removal rate was at pH value 3, but subsequently decreased with the increase of pH value and became negligible at pH value 11. However, polishing experiments using anatase polymorph showed that no material removal was observed for the entire range of pH values. The removal rate of germanium showed a linear relationship with pressure and table speed. Higher removal rate of germanium using rutile abrasive could be attributed to the formation of Ti-*O*-Ge bond due to the structural similarity of polishing surface and abrasive.

Above literatures do not determine manner in which the abrasive removal depth is affected by the chemical reaction of the slurry, the SDFE value for the silicon wafers that are affected by slurry, or the thickness of the chemical reaction layer for a silicon wafer. Therefore, this study uses a cross-groove pattern polishing pad for chemical mechanical polishing (CMP) of a silicon wafer, and uses the polishing pixel calculation model and binary image pixel division and the specific downward force energy (SDFE) theory to construct the theoretic model for wafer abrasive removal depth. Specifically, the theoretical model for abrasive removal

Table 1
Statistical parameter values related to roughness peaks [15].

Parameter	Explanation	Value
Ep [16]	Young's modulus for the polishing pad.	100 *MPa*
σ [17]	The standard deviation for the height distribution for the roughness peaks of the polishing pad.	25 μm
β [17]	The average radius of the roughness peaks of the polishing pad.	30 μm
ν_p [16]	Poisson's ratio for the polishing pad.	0.3
E_w [18]	Young's modulus for the silicon wafer.	161.12 *GPa*
ν_w [18]	Poisson's ratio for the silicon wafer.	0.27
η [16]	The roughness peaks of the area density of the polishing pad.	2×108 m^{-2}

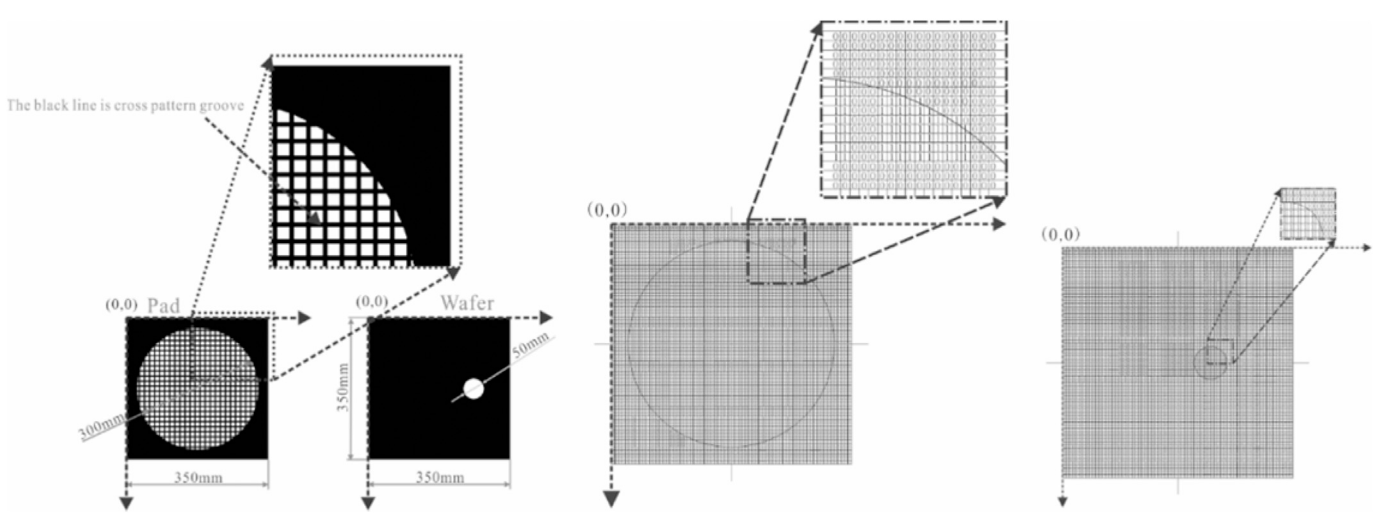

Fig. 2. Binary pixel matrices for the wafer and the cross-groove polishing pad.

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