Determining the Preston Constants of Low-Dielectric-Constant Polymers

by

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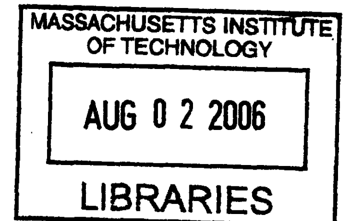

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in partial fulfillment of the requirements for the Degree of
Bachelor of Science in Mechanical Engineering

ABSTRACT

An important step in the manufacture of integrated circuits (ICs) is the Chemical Mechanical Polishing (CMP) process. In order to effectively use CMP, the removal rates of the materials used in ICs must be known. The removal rate of a given material by CMP can be determined once its Preston constant is known. The objectives of this work were to develop a method to determine the Preston constants and to measure the Preston constants of four low-dielectric-constant (low-k) polymers, labeled A, B, C, and D, and Cu. A weight-loss method, which measures the weight difference between the initial wafer and the polished wafer, provided repeatable results. The Preston constants ranged from 1.01 to 5.96 $\times 10^{-13}$ m^2/N. The variation in measurements of the Preston constant ranged from 16% to 31%. The Preston constant of Cu was found to be $1.60 \pm 0.50 \times 10^{-13}$ m^2/N. Of the four polymers, Polymer A had the smallest Preston constant, $1.01 \pm 0.30 \times 10^{-13}$ m^2/N. It was also determined that there is an approximate inverse linear relationship between the Preston constant of the four low-k polymers and their Young's moduli of elasticity. An approximate inverse linear relationship between the Preston constant of the four low-k polymers and the hardness was also observed.

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Table of Contents

Title Page	Page 1
Abstract	2
Acknowledgements	3
Table of Contents	4
List of Figures	5
List of Tables	6
Chapter 1. Introduction	**7**
Chapter 2. Theory of Polishing	**10**
Chapter 3. Experimental Procedures	**12**
3.1 Water-jet Cutting	12
3.2 CMP Experiments	13
Chapter 4. Results	**15**
Chapter 5. Discussion	**21**
Chapter 6. Conclusions	**23**
Appendix	**24**
A.1 Pin-on-Disk Theory	24
A.2 Experimental Procedure	25
A.3 Results	26
A.3.1 CMP Machine	26
A.3.2 Pin-on-Disk Machine	27
A.3.3 Summary	28
A.4 Discussion	28
References	**30**

List of Figures

Figure 1	(a) Al deposition (b) SiO2 deposited onto Al (c) Al and SiO2 after CMP (d) Lithographed SiO2 (e) Cu deposited onto SiO2 (f) Cu and SiO2 after the CMP process.[1]	Page 7
Figure 2	The increase in components per computer chip over time.[3]	8
Figure 3	Schematic of the CMP process.[1]	10
Figure 4	Close-up of the wafer-pad interface during the CMP process.	10
Figure 5	Four 100-mm wafers were cut from each 300-mm wafer.	12
Figure 6	Schematic cross-sections of the 100-mm wafers used in experiments.	12
Figure 7	The rotary CMP Tool used for polishing 100-mm wafers.	14
Figure 8	Relation between the reciprocal Preston constant and Young's modulus of the four low-k polymers.	18
Figure 9	Relation between the reciprocal Preston constant and hardness of the four low-k polymers.	18
Figure 10	Relation between the hardness and Young's modulus of the four low-k polymers.	19
Figure 11	Relation between the reciprocal Preston constant and Young's modulus of the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4.[6] [Cu (Lai), Al, SiO_2 and Si_3N_4 data provided by J.Y. Lai]	19
Figure 12	Relation between the reciprocal Preston constant and hardness of the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4.[6] [Cu (Lai), Al, SiO_2 and Si_3N_4 data provided by J.Y. Lai]	20
Figure A1	Cu and Teflon disks used in the CMP experiment.	25
Figure A2	Setup of Pin-on-Disk experiment.	25
Figure A3	Disks used in Pin-on-Disk experiment.	26

List of Tables

Table 1	CMP experimental conditions.	Page 13
Table 2	Cu CMP results.	15
Table 3	Polymer A CMP results.	15
Table 4	Polymer B CMP results.	16
Table 5	Polymer C CMP results.	16
Table 6	Polymer D CMP results.	17
Table 7	Average Preston constants of Cu and the four polymers.	17
Table 8	Material properties of Cu and the four low-k polymers.	17
Table A1	Summary of CMP experimental conditions.	26
Table A2	Summary of Teflon CMP results.	27
Table A3	Summary of Cu CMP results.	27
Table A4	Summary of Teflon Pin-on-Disk results.	27
Table A5	Summary of Cu Pin-on-Disk results.	27
Table A6	Average Cu and Teflon Preston constants (10^{-13} m^2/N).	28

1. Introduction

In the integrated circuit manufacturing industry, a process called Chemical Mechanical Polishing (CMP) is used to remove material on the order of nanometers. Two different types of CMP are used in the manufacturing of computer chips. The first type of CMP is called inter-level dielectric CMP. This process is shown schematically in Figure 1a-1c. In this process, Al strips are deposited on to a planar surface. A uniform layer of silicon dioxide is then deposited over the Al strips such that the trenches between the Al are filled. Finally, the CMP process is then used to remove the excess SiO_2. The second type of CMP is called metal CMP. This process is shown schematically in Figure 1d-1f. In this process, narrow channels (on the order of hundreds of nanometers) are produced in a thin layer of SiO_2. A thin layer of metal is then deposited over the top of the trenched surface of SiO_2. Then, the CMP process is used to remove the excess metal. In this thesis, a specific type of metal CMP, Cu CMP, is the only type that will be discussed and the term CMP will refer to Cu chemical mechanical polishing. The reason for focusing on Cu CMP is that dishing and erosion occur, which need to be further studied.[1]

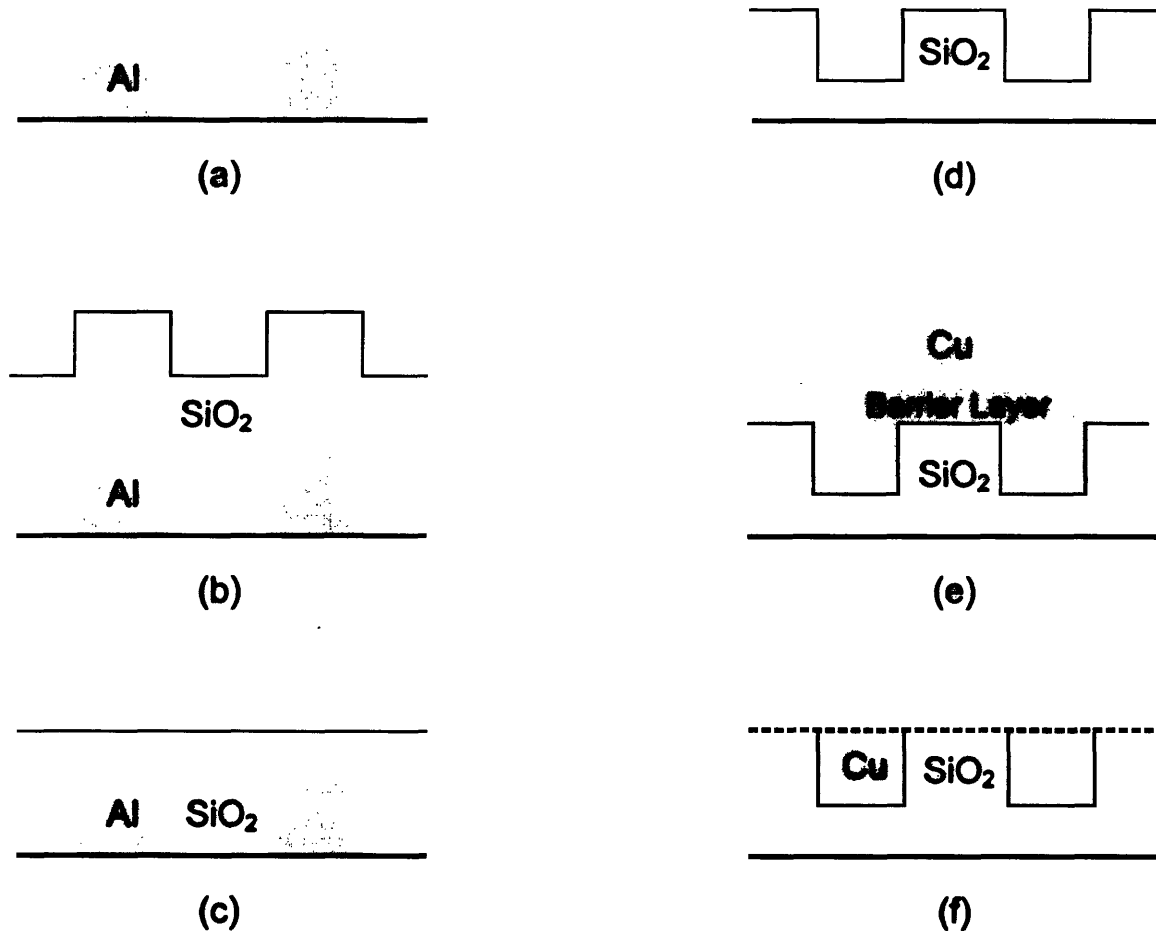

Figure 1: (a) Al deposition **(b)** SiO_2 deposited onto Al **(c)** Al and SiO_2 after CMP **(d)** Lithographed SiO_2 **(e)** Cu deposited onto SiO_2 **(f)** Cu and SiO_2 after the CMP process.[1]

Near the end of the CMP process, when all of the excess Cu has been removed, the polishing process starts to remove both Cu and SiO_2 resulting in dishing and erosion. The ideal goal of CMP is to polish just enough Cu such that a uniform, planar surface remains. However, due to a number of variables, it is very difficult for every point on the polished surface of a patterned wafer to finish planar. As a result, most of the surface experiences over-polishing, which leads to concavities in the Cu channels and the surrounding oxide; dishing and erosion. Dishing and erosion can be minimized if detailed knowledge of the material removal rates is known. In order to calculate the material removal rate of a material, it is necessary to determine the Preston constant.

As the demand for faster computers and processors increases, the number of channels (components) per computer chip will also increase. Figure 2 shows the past and predicted number of components per computer chip. As more components are added, the channel width will decrease along with the spacing between channels. As the channel width decreases and as the spacing between channels decreases, the time delay for a signal to pass through the circuit will increase. One way to counteract the increase in time delay is to decrease the permittivity of the insulating material between the channels. Silicon dioxide has a dielectric constant of about 3.90. The four low-k polymers tested have dielectric constants ranging from 2.20 to 3.05, which is significantly less than the dielectric constant of SiO_2. Therefore, low-k polymers are being developed to replace SiO_2 so that computer chips can be created with more components.[2]

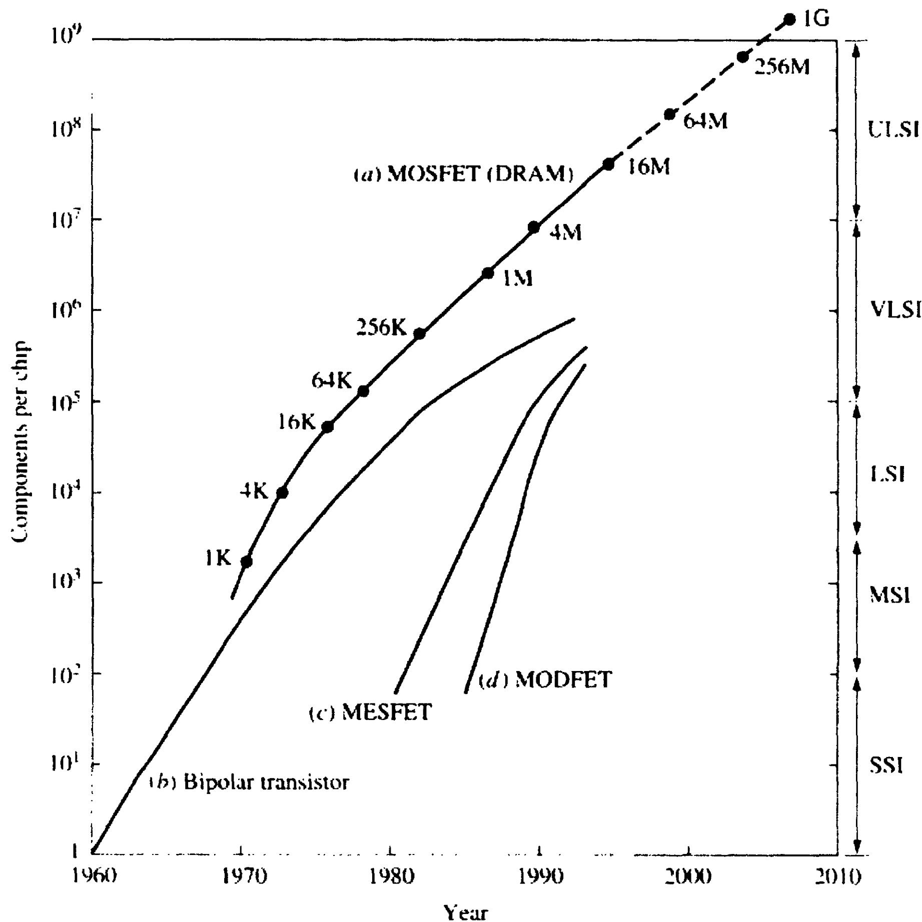

Figure 2: The increase in components per computer chip over time.[3]

Before low-k polymers can be used in computer chips, the accurate Preston constants of the polymers must be known. In this thesis, the Preston constants of four low-k polymers and Cu were determined by the weight-loss method. Chapter 2 develops the theory of polishing and how the material removal rate is related to the Preston constant. Chapter 3 details how the four low-k polymers (labeled A, B, C and D) and Cu, obtained in the form of 300-mm diameter wafers, were cut to produce 100-mm wafers. This chapter also details the procedure of the weight-loss method, and describes the experimental CMP machine. Initially, a Pin-on-Disk machine was used to determine the Preston constant. However, this method produced results with large variations and the results did not match those found in literature. The Appendix details the Pin-on-Disk experiments. Chapter 4 will show the results obtained from the experiments and will display the relationships between the Preston constants and Young's modulus and hardness of specific materials. Finally, in Chapter 5 the results obtained are discussed, followed by important conclusions in Chapter 6.

2. Theory of Polishing

In the CMP process, shown schematically in Figure 3, the wafer is placed on a polishing machine where an abrasive-laden pad removes the excess Cu.

If the angular velocity of the wafer, ω_w, is equal to the angular velocity of the platen, ω_p, the magnitude of the velocity of any point on the wafer relative to the pad, v_r, is independent of its spatial coordinates and time and is given by

$$v_r = r_{cc}\omega_w \tag{1}$$

where r_{cc} is the distance between the centers of the wafer and the of the pad, and ω_w is the angular velocity of the wafer or the pad.

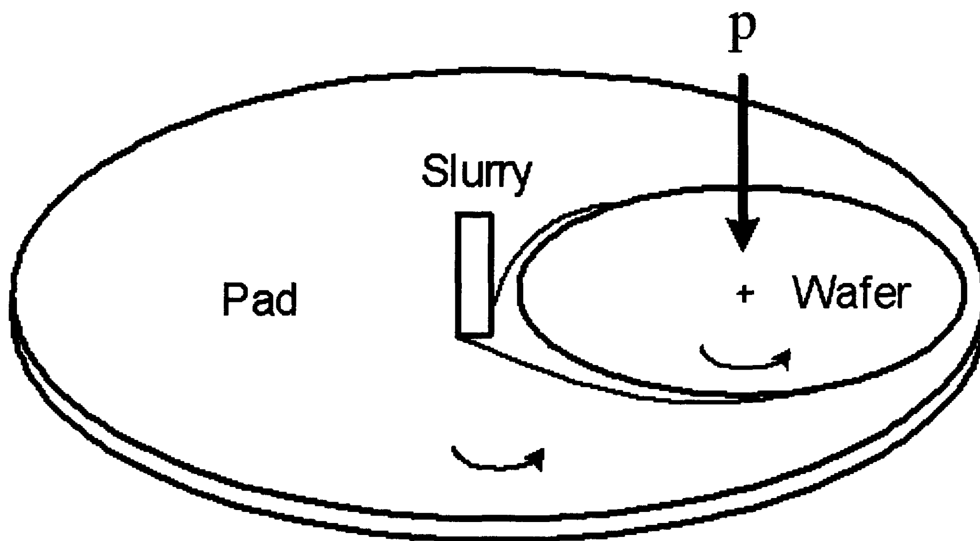

Figure 3: Schematic of the CMP process.[1]

A close-up of the wafer-pad interface is illustrated in Figure 4. It is assumed that every point on the facedown wafer is constantly in contact with the pad and that slurry is regularly delivered to and removed from the wafer/pad interface at a constant rate.

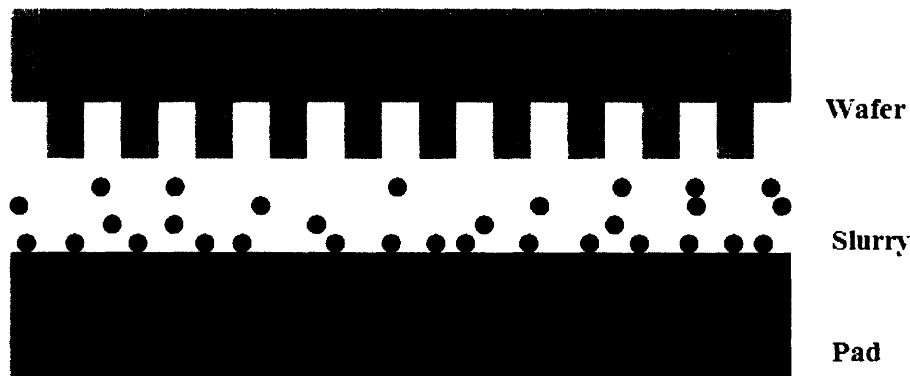

Figure 4: Close-up of the wafer-pad interface during the CMP process.

The linear material removal rate is defined, but for the sign, by the Preston Equation[4] as:

$$MRR = \frac{dh}{dt} = k_p p v_r \tag{2}$$

where h is the height (or thickness) of the film (or wafer), t the time, k_p the Preston constant, and p is the nominal pressure exerted on the wafer. Multiplying both sides of Equation 2 by the surface area of the wafer , A_s

$$\frac{dV}{dt} = k_p p v_r A_s \tag{3}$$

where V is the volume of the coating being polished. Multiplying both sides of Equation 3 by the density, ρ, of the material, the mass removal rate may be expressed as:

$$\frac{dm}{dt} = k_p p v_r A_s \rho \tag{4}$$

where m is the mass of the coating (or wafer). Instead of using the instantaneous mass removal rate, Equation 4 can be rewritten to reflect the change in mass over a given period of time, Δt:

$$\frac{\Delta m}{\Delta t} = k_p p v_r A_s \rho \tag{5}$$

Thus the Preston constant, k_p, is obtained from Equation 5 as:

$$k_p = \frac{\Delta m}{\Delta t (p v_r A_s \rho)} \tag{6}$$

The normalized material removal rate can be expressed as a dimensionless number:

$$NMRR = k_p p \tag{7}$$

Error Analysis

The error in k_p, u_k, is calculated using a 95% confidence interval[5]:

$$u_k = t_{0.025,\upsilon} \frac{S_k}{\sqrt{n}} \tag{8}$$

where n is the number of measurements, S_k is the standard deviation in the Preston constant measurements, and $t_{0.025,\upsilon}$ is the corresponding value for a 95% confidence t-distribution.

3. Experimental Procedures

3.1 Water-Jet Cutting

The wafers obtained were 300 mm in diameter. Figure 5 shows that four 100-mm wafers were cut from each of the 300-mm wafers by a water-jet cutter, Omax Model 2652. Prior to cutting, a 300-mm wafer was attached to a 400 mm x 400 mm x 6 mm Al plate with double-sided adhesive tape. The Al plate provided a solid backing for the wafers during the cutting process. For additional protection, a 400 mm x 400 mm x 1 mm polystyrene sheet was placed over the wafer during cutting. This created a sandwich effect that protected the wafer against fracture during water-jet cutting. During the cutting process, the sandwiched materials were held in place by four lead blocks. The water-jet was set to cut through 6 mm Al at the slowest possible cutting speed. The water-jet abrasive used was grade 80 garnet. Schematics of the 100-mm wafer cross-sections are shown in Figure 6.

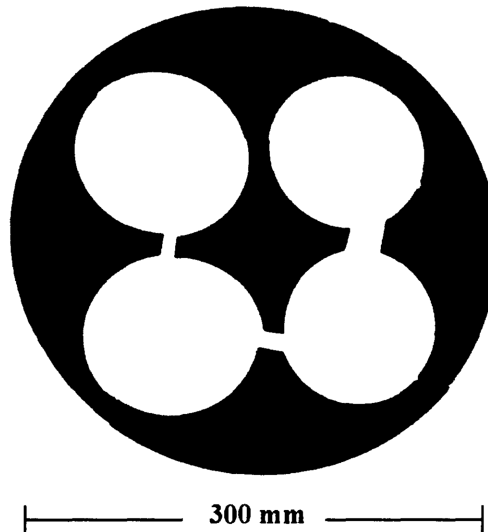

Figure 5: Four 100-mm wafers were cut from each 300-mm wafer.

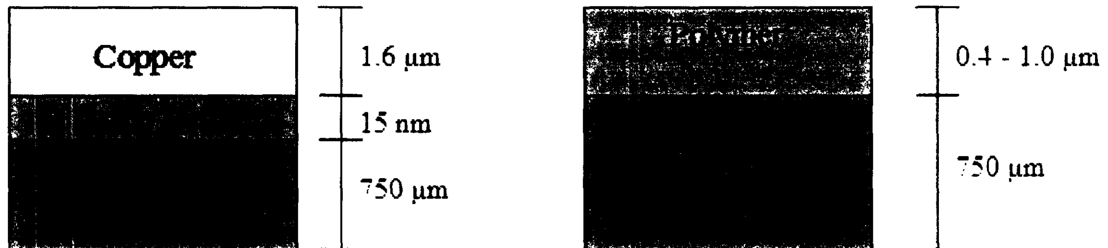

Figure 6: Schematic cross-sections of the 100-mm wafers used in experiments.

3.2 CMP Experiments

The CMP tool employed for polishing the wafers is shown in Figure 7. A wafer holder was used to support the Cu and the low-k polymer wafers. An abrasive-laden, Rohm and Haas IC1000 pad with a Suba IV subpad was used to remove the material on the wafer. Both the wafer holder and the polishing pad were rotated at the same speed by their respective drive motors. A gravity-fed slurry dispenser was used to control slurry flow rate. A pneumatic cylinder-piston assembly applied the normal force on the wafers. A computer was used to control the rotational speeds of both the wafer and platen motors. The speeds and directions of both motors were controlled to be the same. The computer was also used to control the pistons that exerted pressure on the wafer. The experimental parameters are listed in Table 1. The slurry employed was the alumina-based, commercial Cabot i-Cue 5001 slurry. An electronic stopwatch was used to record the duration of the experiment.

Table 1: CMP experimental conditions.

Diameter of wafer (mm)	100
Pressure (kPa)	22.1
Velocity (m/s)	0.56
Slurry Flow Rate (ml/min)	100

The wafers were weighed before and after the experiment and the differences were used in Equation 6 to calculate the Preston constant. The weighed masses ranged from approximately 9 g to 15 g. The difference in masses ranged from approximately 0.40 mg to 40.0 mg. The relative velocity was calculated by Equation 1, using the angular velocities of the pad and wafer motors. The pressure was recorded by the computer and was used in Equation 6. This process was repeated many times for Cu and the four low-k polymers. The densities of the materials are listed in Table 8.

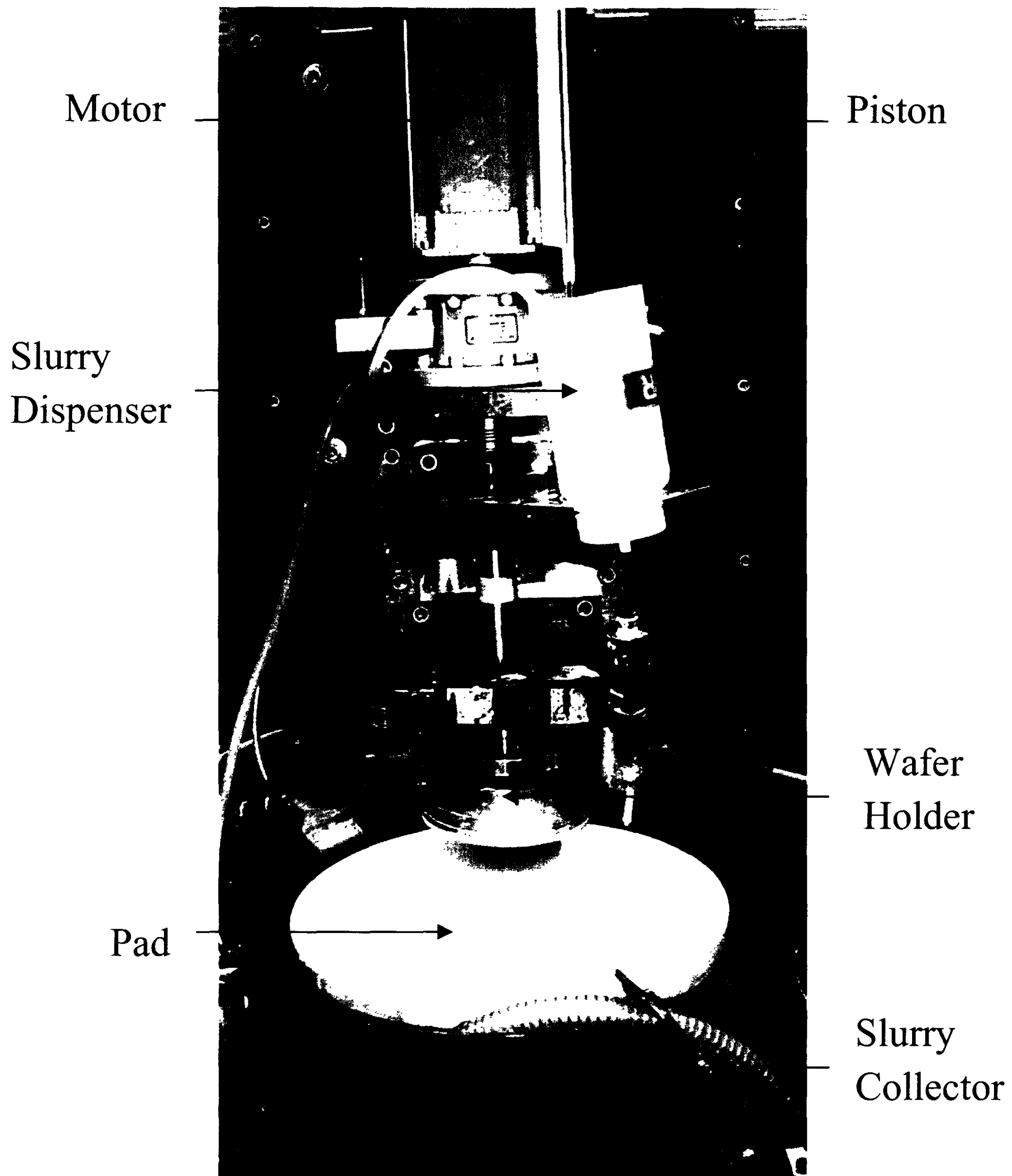

Figure 7: The rotary CMP Tool used for polishing 100-mm wafers.

4. Results

The results of the Cu CMP experiments are summarized in Table 2 and the results of the polymer experiments are summarized in Tables 3 through 6. The mean Preston constants for Cu and the four low-k polymers are listed in Table 7. The material properties of the four low-k polymers and Cu are listed in Table 8.

Table 2: Cu CMP results.

Test	Δt	m_i	m_f	Δm	Δh	MRR	NMRR	k_p
	(s)	(g)	(g)	(mg)	(nm)	(nm/s)	(nm/m)	(10^{-13} m^2/N)
Cu 1	30	9.57940	9.57725	2.15	31	1.02	1.83	0.83
Cu 2	60	9.58383	9.57940	4.43	63	1.05	1.88	0.85
Cu 3	150	9.61198	9.59505	16.93	241	1.61	2.88	1.30
Cu 4	240	9.57725	9.56629	10.96	156	0.65	1.17	0.53
Cu 5	30	9.55146	9.54793	3.53	50	1.68	3.00	1.36
Cu 6	90	9.53520	9.52516	10.04	143	1.59	2.85	1.29
Cu 7	150	9.50112	9.48016	20.96	299	1.99	3.57	1.62
Cu 8	270	9.48035	9.44807	32.28	460	1.70	3.05	1.38
Cu 9	60	9.51717	9.50571	11.46	163	2.72	4.88	2.21
Cu 10	120	9.61200	9.59159	20.41	291	2.43	4.34	1.97
Cu 11	210	9.70180	9.67437	27.43	391	1.86	3.33	1.51
Cu 12	150	14.23371	14.19738	36.33	518	3.45	6.18	2.80
Cu 13	150	14.18860	14.14762	40.98	584	3.90	6.97	3.16

Table 3: Polymer A CMP results.

Test	Δt	m_i	m_f	Δm	Δh	MRR	NMRR	k_p
	(s)	(g)	(g)	(mg)	(nm)	(nm/s)	(nm/m)	(10^{-13} m^2/N)
A 1	120	13.681602	13.679378	2.22	210	1.75	3.13	1.42
A 2	120	13.626720	13.625008	1.71	162	1.35	2.41	1.09
A 3	120	13.631428	13.629718	1.71	161	1.34	2.41	1.09
A 4	120	13.667600	13.666636	0.96	91	0.76	1.36	0.61
A 5	120	13.603550	13.600600	2.95	278	2.32	4.15	1.88
A 6	120	13.612008	13.611410	0.60	56	0.47	0.84	0.38
A 7	120	13.650120	13.648670	1.45	137	1.14	2.04	0.92
A 8	120	13.653270	13.652010	1.26	119	0.99	1.77	0.80
A 9	120	13.623820	13.622410	1.41	133	1.11	1.98	0.90

Table 4: Polymer B CMP results.

Test	Δt	m_i	m_f	Δm	Δh	MRR	NMRR	k_p
	(s)	(g)	(g)	(mg)	(nm)	(nm/s)	(nm/m)	(10^{-13} m^2/N)
B 1	120	14.132330	14.130202	2.13	217	1.81	3.24	1.47
B 2	120	14.119322	14.117882	1.44	147	1.22	2.19	0.99
B 3	120	14.026212	14.024518	1.69	173	1.44	2.58	1.17
B 4	120	14.122708	14.121270	1.44	147	1.22	2.19	0.99
B 5	120	14.024508	14.022830	1.68	171	1.43	2.55	1.16
B 6	120	14.072882	14.072012	0.87	89	0.74	1.32	0.60
B 7	120	14.106590	14.105468	1.12	114	0.95	1.71	0.77
B 8	120	14.057880	14.056910	0.97	99	0.82	1.47	0.67
B 9	120	14.072882	14.069502	3.38	344	2.87	5.14	2.33
B 10	120	14.033636	14.030722	2.91	297	2.47	4.43	2.01
B 11	120	14.027104	14.025026	2.08	212	1.76	3.16	1.43
B 12	120	14.074690	14.073940	0.75	76	0.64	1.14	0.52
B 13	120	14.077200	14.075050	2.15	219	1.83	3.27	1.48

Table 5: Polymer C CMP results.

Test	Δt	m_i	m_f	Δm	Δh	MRR	NMRR	k_p
	(s)	(g)	(g)	(mg)	(nm)	(nm/s)	(nm/m)	(10^{-13} m^2/N)
C 1	60	14.053140	14.049770	3.37	343	5.72	10.25	4.64
C 2	60	14.113660	14.110602	3.06	312	5.19	9.30	4.21
C 3	30	14.017716	14.015924	1.79	183	6.09	10.90	4.94
C 4	30	14.081850	14.079232	2.62	267	8.89	15.92	7.21
C 5	30	14.132990	14.129760	3.23	329	10.97	19.64	8.90
C 6	15	14.068770	14.067412	1.36	138	9.23	16.52	7.48
C 7	15	14.036566	14.035466	1.10	112	7.47	13.38	6.06
C 8	15	14.093624	14.092758	0.87	88	5.88	10.53	4.77
C 9	15	14.003032	14.001758	1.27	130	8.66	15.50	7.02
C 10	15	14.105824	14.105036	0.79	80	5.35	9.58	4.34

Table 6: Polymer D CMP results.

Test	Δt	m_i	m_f	Δm	Δh	MRR	NMRR	k_p
	(s)	(g)	(g)	(mg)	(nm)	(nm/s)	(nm/m)	(10^{-13} m^2/N)
D 1	30	14.190108	14.188822	1.29	159	5.30	9.49	4.30
D 2	10	14.127770	14.127260	0.51	63	6.31	11.29	5.11
D 3	15	14.207150	14.206556	0.59	73	4.90	8.77	3.97
D 4	10	14.139254	14.138402	0.85	105	10.54	18.86	8.54
D 5	10	14.162504	14.162032	0.47	58	5.84	10.45	4.73
D 6	10	14.117604	14.117094	0.51	63	6.31	11.29	5.11
D 7	10	14.131584	14.131066	0.52	64	6.41	11.47	5.19

Table 7: Average Preston constants of Cu and the four polymers.

Material	k_p (10^{-13} m^2/N)
Cu	1.60 ± 0.50
Polymer A	1.01 ± 0.30
Polymer B	1.20 ± 0.31
Polymer C	5.96 ± 0.96
Polymer D	5.28 ± 1.13

Table 8: Material properties of Cu and the four low-k polymers.

Name	K	RI	Density	E-nano	H-nano	Porosity	Thickness	k_p
		@ 673nm	(kg/m^3)	(GPa)	(GPa)	(%)	(µm)	(10^{-13} m^2/N)
Cu			8,930	128.0	1.22		1.6	1.60
A	3.05	1.42	1,350	11.1	2.09	6.7	1.0	1.01
B	2.50	1.33	1,250	8.0	1.37		1.0	1.20
C	2.50	1.41	1,250	9.0	1.47		1.0	5.96
D	2.20	1.25	1,030	3.9	0.53	37.0	0.4	5.28

The relation between the reciprocal of the Preston constant and Young's modulus of the four polymers is shown in Figure 8. The relation between the reciprocal Preston constant and hardness of the four polymers is shown in Figure 9. The reason for plotting the reciprocal of Preston constant, instead of the Preston constant itself, versus modulus and hardness is that all of these quantities have the same unit, N/m^2.

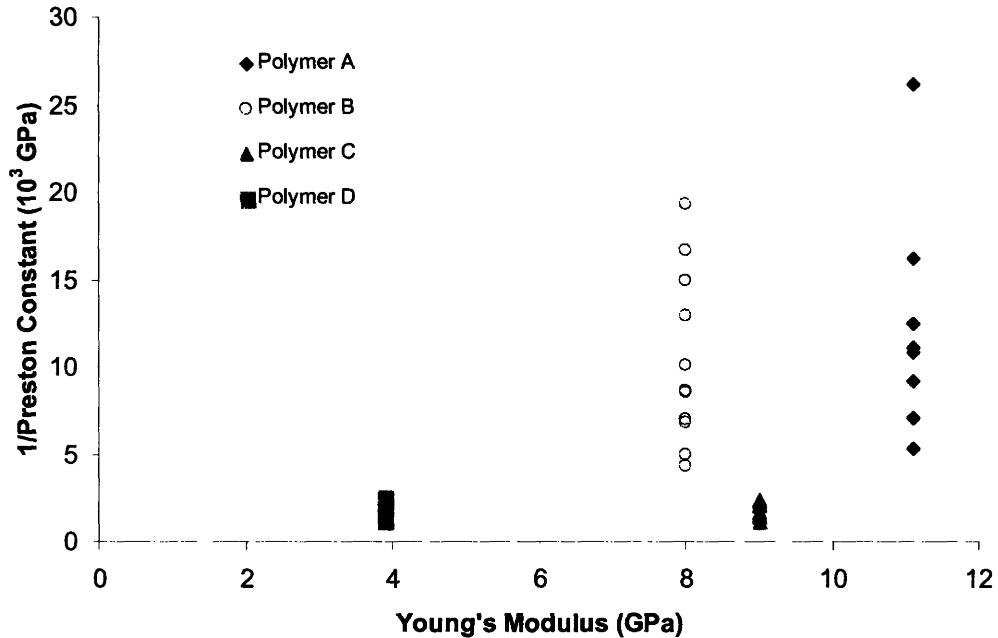

Figure 8: Relation between the reciprocal Preston constant and Young's modulus of the four low-k polymers.

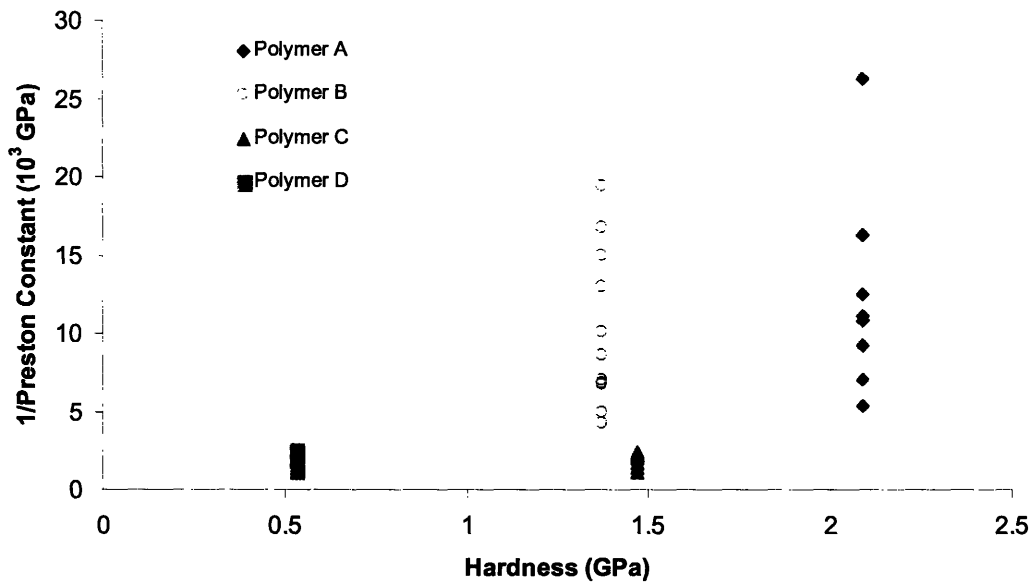

Figure 9: Relation between the reciprocal Preston constant and hardness of the four low-k polymers.

The relation between the hardness and the Young's modulus of the four polymers is shown in Figure 10.

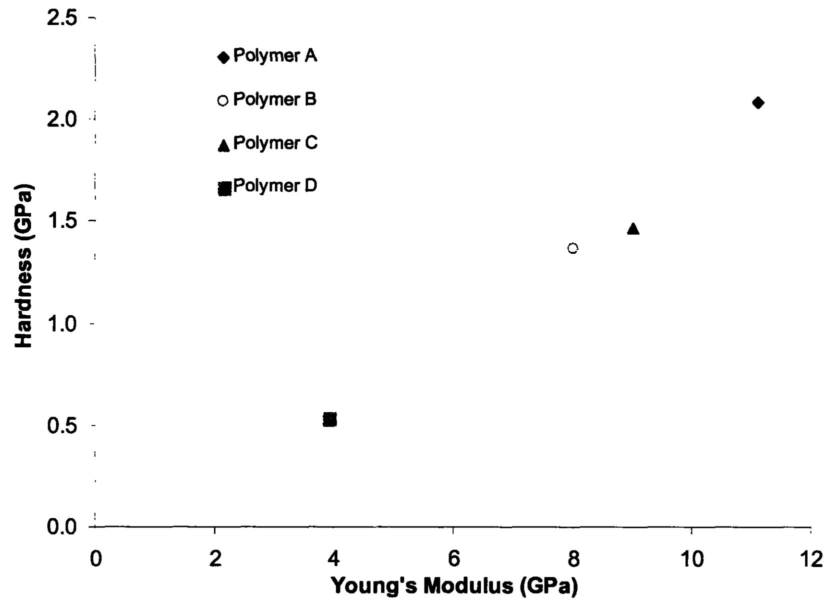

Figure 10: Relation between the hardness and Young's modulus of the four low-k polymers.

Figure 11 shows the relation between the reciprocal of the Preston constant and Young's modulus of the four polymers, Cu, Al, SiO_2 and Si_3N_4. The relation between the reciprocal Preston constant and hardness of the four polymers, Cu, Al, SiO_2 and Si_3N_4 is shown in Figure 12.

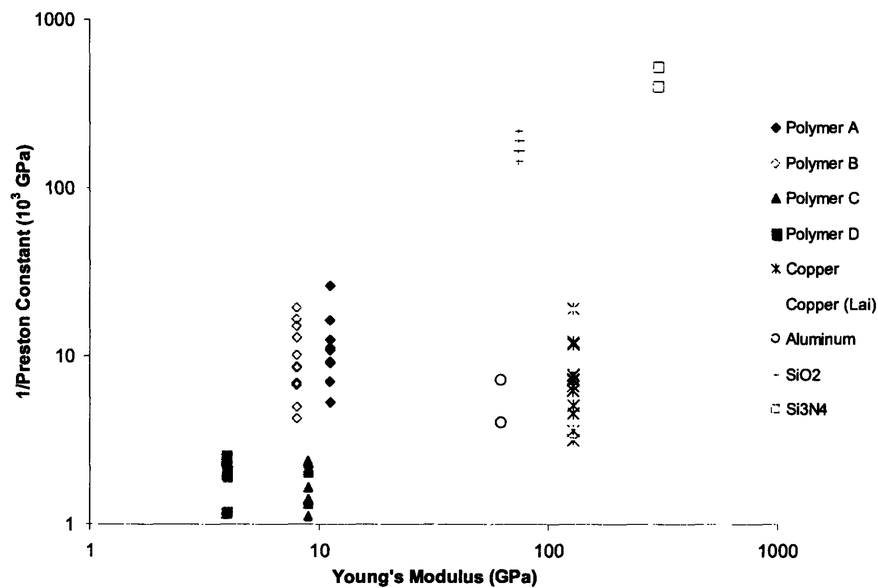

Figure 11: Relation between the reciprocal Preston constant and Young's modulus of the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4.[6] [Cu (Lai), Al, SiO_2 and Si_3N_4 data provided by J.Y. Lai]

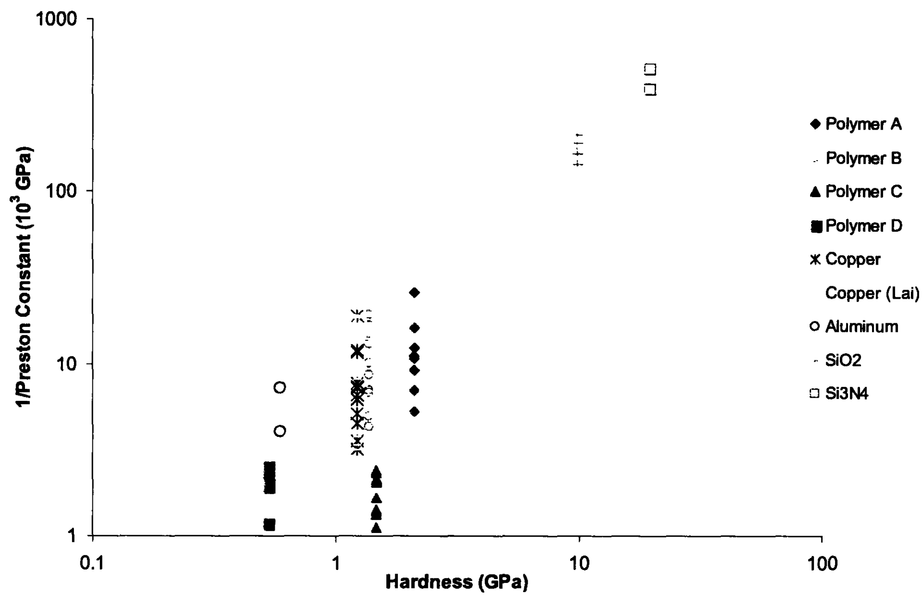

Figure 12: Relation between the reciprocal Preston constant and hardness of the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4.[6] [Cu (Lai), Al, SiO_2 and Si_3N_4 data provided by J.Y. Lai]

5. Discussion

The two primary objectives of this work were to develop a method that determines the Preston constant of IC material and to measure the Preston constants of four low-dielectric-constant (low-k) polymers, labeled A, B, C, and D, and Cu.

A method to cut 100-mm wafers out of 300-mm wafers was developed, using a water-jet cutter. Using a 6-mm thick Al plate and a protective layer of polystyrene, the 300-mm wafers were successfully supported so that 100-mm wafers could be obtained. The weight-loss method was successfully used to determine the value of the Preston constants and subsequently the material removal rates of four low-k polymers and Cu. Table 7 shows the variation in the Preston constants for the four low-k polymers and Cu. Cu has the largest variation in Preston constant with 31%. Polymer C has the smallest variation in Preston constant with 16%. Therefore, the variations in Preston constant ranged from 16% to 31%. Occasionally during the polishing process, small flakes of material would peel off of the wafers. This is not a direct result of the CMP process, but has more to do with the handling of wafers. It is possible that during the cutting process some of the material was dislodged, which then fell off during the polishing process. These lost flakes of material could account for some of the variation in the Preston constant values. In addition, the percent variation in Preston constant values is fairly consistent for the four polymers and Cu. This suggests that the variation is systematically present in the procedure and repeatedly occurs. This would also support the conclusion that during the cutting process, some of the material is routinely dislodged and subsequently falls off during the CMP process.

The Preston constants of four low-k polymers and Cu were determined. The material properties of the four polymers and Cu can be found in Table 8. The values of the Preston constant ranged from 1.01 to 5.96 $\times10^{-13}$ m^2/N. Table 7 shows the average Preston constants of the four low-k polymers and Cu. Polymer A had the smallest average Preston constant with a value of $1.01 \pm 0.30 \times10^{-13}$ m^2/N. Polymer B had the second smallest average Preston constant with a value of $1.20 \pm 0.31 \times10^{-13}$ m^2/N. Cu had the next largest average Preston constant with a value of $1.60 \pm 0.50 \times10^{-13}$ m^2/N. Polymer D had the next largest average Preston constant with a value of $5.28 \pm 1.13 \times10^{-13}$ m^2/N. Finally, Polymer C had the largest average Preston constant with a value of $5.96 \pm 0.96 \times10^{-13}$ m^2/N. With this information, it is recommended that Polymer A or Polymer B be used to replace SiO_2 from a manufacturing point of view. In the chemical mechanical polishing process it is desirable for the insulating material to have a lower material removal rate than Cu because then the insulating material will provide a hard-stop that will prevent the chip from being over polished and minimize dishing and erosion. Of the four low-k polymers tested, Polymer A and Polymer B both had Preston constants lower than the Preston constant of Cu. As Equation 2 shows, assuming that the Cu and insulating material experience the same pressure and velocity, if the insulating material has a Preston constant smaller than Cu, then its material removal rate will also be smaller than Cu's material removal rate.

It was determined that there is an approximate inverse relationship between the Preston constant of the polymers and the Young's modulus of the polymers, as implied by the linear relationship between the reciprocal of the Preston constant and the modulus, seen in Figure 8. Similarly, Figure 9 shows that there is an inverse relationship between the Preston constants of the polymers and their hardness. Figure 10 shows that there is a linear relationship between the

hardness and Young's modulus of the four polymers. This is expected because the hardness and Young's modulus are in general linearly dependent on each other. Figure 11 shows that there is an approximate inverse linear relationship between the Preston constant and Young's modulus of eight different integrated circuit materials (the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4). Figure 12 shows that there is an approximate inverse linear relationship between the Preston constant and hardness of eight different integrated circuit materials (the four low-k polymers, Cu, Al, SiO_2 and Si_3N_4). Therefore, it is observed that there exists an approximate inverse linear relationship between the Preston constant and Young's modulus, and between the Preston constant and hardness. This approximate relationship cannot be made more accurate because the Preston constant takes into account both chemical and mechanical properties, whereas Young's modulus and hardness are mechanical properties. The chemical properties that the Preston constant reflects are heavily dependent upon the type of slurry used in the CMP process, which is another variable added into this equation. Therefore, a more specific relationship cannot be obtained.

6. Conclusions

A method of determining the Preston constant and material removal rate of integrated circuit material was successfully established. Using the method, the Preston constants of four low-k polymers and Cu were determined. The variation in the Preston constant values ranged from 16% to 31%. The values of the Preston constant for the four low-k polymers ranged from 1.01 to 5.96×10^{-13} m^2/N. The average Preston constant of Cu was determined to be 1.60×10^{-13} m^2/N. It was determined that there is an approximate inverse relationship between the Preston constant of the polymers and the Young's modulus of the polymers. It was further established that there is an approximate inverse relationship between the Preston constants of the polymers and their hardness.

Appendix:
A Study of the Material Removal Rate by a Pin-on-Disk Machine

An alternative method used to determine the Preston constant was a Pin-on-Disk machine. Experiments were conducted to compare the Preston constants obtained with a Pin-on-Disk machine and an experimental CMP machine. The Preston constants of Teflon and Cu were compared. It was subsequently determined that results provided by the Pin-on-Disk machine had a large variation and did not match results found in literature. Therefore, the Pin-on-Disk results were not used in the thesis. Nevertheless, the Pin-on-Disk theory, experimental procedure, results and discussion are found in this appendix.

A.1 Pin-on-Disk Theory

Instead of using the instantaneous change in height in Equation 2, the material removal rate can be defined as:

$$MRR = \frac{\Delta h}{\Delta t} = k_p p v_r \tag{A1}$$

where h is the height (thickness) of the pin, t is time, k_p is the Preston constant, p is the pressure that is exerted on the pin, and v_r is the relative velocity of the pin. If both sides of Equation A1 are multiplied by the nominal surface area of the pin, Equation A2 is obtained:

$$\frac{\Delta V}{\Delta t} = k_p F v_r \tag{A2}$$

where F is the force exerted on the pin. If both sides of Equation A2 are multiplied by Δt, Equation A3 is obtained:

$$\Delta V = k_p F s \tag{A3}$$

where s is the distance traveled by the pin. Equation A3 can be solved for the Preston constant:

$$k_p = \frac{\Delta V}{Fs} \tag{A4}$$

If the density, ρ, and mass, m, of the pin are substituted into Equation A4 for volume, V, Equation A5 is obtained:

$$k_p = \frac{\Delta m}{Fs\rho} \tag{A5}$$

A.2 Experimental Procedure

The apparatus for the CMP machine is shown in Figure 7 and is the same as that described in Section 3.2. The wafer holder was used to support 100-mm diameter disks of Cu and Teflon as seen in Figure A1. The procedure for the CMP machine is the same as the procedure described in Section 3.2.

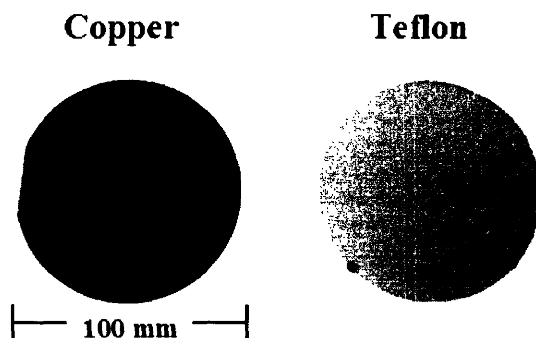

Figure A1: Cu and Teflon disks used in the CMP experiment.

The apparatus for the Pin-on-Disk machine is shown in Figure A2. A pin holder was used support the Cu and Teflon 12.7-mm diameter disks, seen in Figure A3. An abrasive pad was used to remove the excess material on the disks. The abrasive pad was rotated by a speed-controlled DC motor. A slurry holder was used to hold the fixed amount of slurry. A weight holder was used to apply pressure to the specimens.

Figure A2: Setup of Pin-on-Disk experiment.

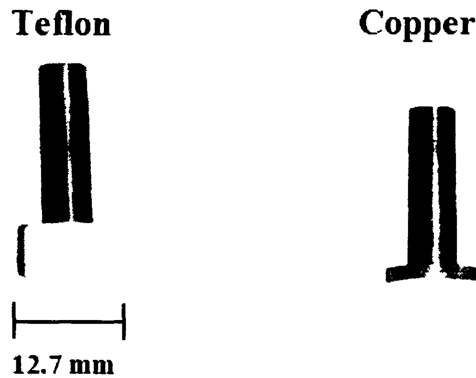

Figure A3: Disks used in Pin-on-Disk experiment.

A pin and small "disk", as seen in Figure A3, were inserted into the pin holder. Weights of known mass were manually added to the weight holder to apply pressure to the disks. The slurry holder was filled with Cabot brand i-Cue 5001 slurry. The rotational speed of the abrasive pad was set manually. A stop-watch was used to record the duration of the experiment. The disk was weighed both before and after the experiment and the initial and final masses were recorded to be used in Equation A5. The total distance traveled by the pin was obtained by multiplying the velocity by time. This was also recorded and used in Equation A5.

A.3 Results

For all calculations, the density of Cu was taken as 8,960 kg/m^3 and the density of Teflon was given as 2,200 kg/m^3.

A.3.1 CMP Machine

All CMP experiments were conducted with the conditions specified in Table A1. The results for the Teflon CMP experiments are summarized in Table A2. The results for the Cu CMP experiments are summarized in Table A3.

Table A1: Summary of CMP experimental conditions.

	Cu	Teflon
Diameter of disk (mm)	100	100
Pressure (kPa)	27.6	27.6

Table A2: Summary of Teflon CMP results.

Test	Δt	m_i	m_f	Δm	v_r	MRR	k_p
	(s)	(g)	(g)	(g)	(m/s)	(nm/s)	(10^{-13} m^2/N)
1	507	70.870	70.840	0.030	0.698	3.42	1.79
2	660	70.815	70.675	0.140	0.698	12.28	6.38
3	300	116.732	116.714	0.018	0.698	3.38	1.76
4	600	116.714	116.704	0.010	0.698	1.01	0.52
5	180	116.704	116.690	0.014	0.698	4.54	2.36
6	900	116.897	116.871	0.026	0.931	1.67	0.65

Table A3: Summary of Cu CMP results.

Test	Δt	m_i	m_f	Δm	v_r	MRR	k_p
	(s)	(g)	(g)	(g)	(m/s)	(nm/s)	(10^{-13} m^2/N)
1	900	81.719	80.698	1.021	0.931	16.12	6.28

A.3.2 Pin-on-Disk Machine

The results for the Teflon Pin-on-Disk experiments are summarized in Table A4. The results for the Cu Pin-on-Disk experiments are summarized in Table A5.

Table A4: Summary of Teflon Pin-on-Disk results.

Test	m_i	m_f	Δm	F	s	MRR	k_p
	(g)	(g)	(g)	(N)	(m)	(nm/s)	(10^{-13} m^2/N)
1	1.655	1.647	0.009	4.905	766	13.37	10.81
2	1.516	1.511	0.005	4.905	479	14.49	10.05
3	1.601	1.599	0.002	4.905	395	6.86	4.04

Table A5: Summary of Cu Pin-on-Disk results.

Test	m_i	m_f	Δm	F	s	MRR	k_p
	(g)	(g)	(g)	(N)	(m)	(nm/s)	(10^{-13} m^2/N)
1	7.14032	7.14013	0.0002	4.905	383	0.09	0.11
2	7.14000	7.13853	0.0015	8.829	790	0.54	0.24
3	7.13876	7.13412	0.0046	6.867	1317	1.14	0.57
4	1.55578	1.55480	0.0010	4.905	395	0.96	0.56
5	1.55488	1.54243	0.0124	4.905	1939	1.35	1.46

A.3.3 Summary

The average Preston constants for Teflon and Cu are seen in Table A6.

Table A6: Average Cu and Teflon Preston constants (10^{-13} m^2/N).

	CMP	**Pin-on-Disk**
Teflon	2.24 ± 2.14	8.30 ± 6.82
Cu	6.28	0.59 ± 0.61

A.4 Discussion

The Preston constant of Teflon for the Pin-on-Disk machine was determined to be 8.30 ± 6.82 x10^{-13} m^2/N. The Preston constant of Teflon for the CMP machine was determined to be 2.24 ± 2.14 x10^{-13} m^2/N. The Preston constant of Cu for the Pin-on-Disk machine was determined to be 0.59 ± 0.61 x10^{-13} m^2/N. The Preston constant of Cu for the CMP machine was determined to be 6.28 m^2/N. The average Preston constant of Teflon for the Pin-on-Disk machine is approximately 3.7 times larger than the average Preston constant of Teflon for the CMP machine. The average Preston constant of Cu for the Pin-on-Disk machine is approximately 10.6 times smaller than the average Preston constant for Cu for the CMP machine. Ideally, the value of the Preston constant obtained with the CMP machine should be the same as that obtained with the Pin-on-Disk machine. However, there are many reasons that explain why the Preston constant values do not match. Most notably, the variations in all of the measurements are very large; on the order of the measurements themselves. With variations as large as these, it is expected that the values will not match.

There are a number of factors that could account for the large variation in the Preston constant results. First, the slurry consumption rate for the CMP experiments was not held constant. The value of the Preston constant can greatly vary with amount of slurry consumed. In addition, the samples used in the Pin-on-Disk experiments had much better interaction with the slurry because the small "disks" were always submerged in a pool of slurry. For the CMP experiments, the slurry may not always have been in contact with the bottom of the wafer. This could account for part of the large variations in the value of the Preston constants because the Preston constant includes the chemical effects of the slurry. Second, the test specimens shown in Figures A1 and A3 were not used for all experiments. Some of the experiments used wafers and small disks from different Cu and Teflon stock. This variation in materials could account for some of the large variations in the value of the Preston constants. Third, in some of the experiments, hydrogen peroxide was not added to the slurry. This difference in the chemical properties of the slurry could account for some of the large variations in the value of the Preston constant. Fourth, different scales were used to measure the mass of the samples. Variations in the accuracy of each scale could account for some of the variations in the value of the Preston constants.

As a result of these large variations, it is recommended that these experiments be conducted again with some modifications so that the variations can be reduced. First, the specific stock of Cu and Teflon selected should be of high purity. This means that the Cu tested should not be a Cu alloy and that the Teflon tested should not be coated with a different polymer or of different molecular weight. Second, the same samples should be used for every experiment. Third, the same scale should be used to measure the mass of each sample for every experiment. Fourth, the slurry consumption rate for all experiments should be the same. Fifth, the chemical properties of the slurry should be held constant for all experiments. This means that the amount of hydrogen peroxide added to the slurry should be constant for all experiments.

Despite the large differences between the CMP and Pin-on-Disk Preston constant measurements, it appears that under controlled conditions both methods would provide the same values for the Preston constant. Given all of the factors that could account for the differences, the Preston constant values for Teflon were only off by a factor of 3.7 and Preston constant values for Cu were only off by a factor of 10.6. It is believed that these factors could be drastically reduced under more controlled conditions.

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