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TABLE OF CONTENTS

Overview of SEMI and the IEEE

Keynote Address: Semiconductor Manufacturing: Transition from a Technology Driven to an Economic Driven †
Infrastructure, James Hines, *Dataquest, Inc.*

Yield Modeling & Analysis

Predictive Yield Modeling for Reconfigurable Memory Circuits 1
Dennis Ciplickas and Xiaolei Li, *Rakesh Vallishayee, PDF Solutions, Inc.*; Andrzej Strojwas, *Carnegie Mellon University*;
Randy Williams and Michael Renfro, *Intel Corp.*; Raman Nurani, *KLA-Tencor Corp.*

Analysis and Modeling of Systematic and Defect Related Yield Issues During Early Development of a New Technology 7
R. Guldi, J. Watts, S. PapaRao, D. Catlett, J. Montgomery and T. Saeki, *Texas Instruments Inc.*

How to Simultaneously Reduce α and β Error with SPC? A Multi-Variate Process Control Approach 13
R. Nasongkhla, J. George Shanthikumar, *U.C. Berkeley*; R. Nurani, *KLA-Tencor*; M. McIntyre, *Advanced Micro Devices*

Yield Analysis and Data Management Using Yield Manager™ 19
F. Lee, *Motorola*; S. Smith, *Knights Technology*

A Comparison of Critical Area Analysis Tools 31
Sean Fitzpatrick, Geoffrey O'Donoghue and Gary Check, *Analog Devices, Inc.*

Wafer Line Productivity Optimization in a Multi-Technology Multi-Part-Number Fabricator 34
D. Maynard, R. Rosner, M. Kerbaugh, R. Hamilton, J. Bentlage and C. Boye, *IBM Microelectronics Division*

Overall Equipment Efficiency

The Advantages of Using Short Cycle Time Manufacturing (SCM) Instead of Continuous Flow Manufacturing (CFM) 43
Donald Martin, *IBM Microelectronics Division*

Improvement of AME 8110 Oxide Etcher Daily Clean 50
Kevin Welp, Paul Fisher, Joan Holden, Ping Wang, Mynetta Gunn and Jennie Franco, *Motorola Inc.*

Semiconductor Metrics: Conflicting Goals or Increasing Opportunities? 55
Linda Sattler, *National Microelectronics Research Center*; Robert Schlueter, *Texas Instruments Inc.*

Towards Real-Time Fault Identification in Plasma Etching Using Neural Networks 61
Benyong Zhang and Gary May, *Georgia Institute of Technology*

Control Methods for the Chemical-Mechanical Polishing Process in Shallow Trench Isolation 66
Yutong Wu, Jim Gilhooly and Brett Philips, *IBM Microelectronics Division*

A80 – A New Perspective on Predictable Factory Performance 71
Calum Cunningham and Richard Babikian, *Intel Ireland*

Yield Enhancement Strategies & Techniques

Statistical Methodology for Yield Enhancement via Baseline Reduction 77
K. Fridgeirsdottir and R. Akella, *Stanford University*; M. Li, P. McNally and S. Mittal, *Intel Corp.*

Development of New Methodology and Technique to Accelerate Region Yield Improvement 82
K. Wong, P. Mitchell, J. Nulty, M. Carpenter, L. Kavan, B. Jin, G. McMahon, C. Seams, J. Fewkes, A. Gordon and
C. Sandstrom, *Cypress Semiconductor*

Correlation of Digital Image Metrics to Production ADC Matching Performance 86
Jennifer Blais, *IBM Microelectronics*, Verlyn Fischer, Yoel Moalem, Matthew Saunders, *KLA-Tencor Corp.*

Intelligent Line Monitor: Maximum Productivity Through an Integrated and Automated Line Monitoring Strategy 93
Tom Pilon, *IBM Microelectronics Division*; Mark Burns, Verlyn Fischer and Matthew Saunders, *KLA-Tencor Corp.*

Defect Inspection Sampling Plans: Which One Is Right For Me? 103
Brian Scanlan, *Analog Devices B.V.*

Sampling Methodology for SEM-based Defect Classification: Risk, Cost and Benefit Analysis 109
Ram Akella and Chih-Hung Lin, *Stanford University*; Prasanna Chitturi, *Applied Materials, Inc.*

† Not available at time of printing

Harnessing & Developing Workforce Potential

The Effect of Performance Based Incentive Plans Tim Ingersoll, <i>Texas Instruments, Inc.</i>	115
Enhancing Fab Performance Under Team Council Methodology Ronald N. Dupuis, Jr., John Gervais and Stevan Park, <i>Fairchild Semiconductor</i>	119
Risk Management Exercise in a Wafer Fab Utilizing Dynamic Simulation Todd McCay and Gary DePinto, <i>Motorola, Inc.</i>	122
Rewards, Structure and Alignment Affect Goal Attainment Janet Gentleman-Ingersoll, <i>Texas Instruments, Inc.</i>	128
Quantifying Capacity Loss Associated With Staffing in a Semiconductor Manufacturing Line C. Pollitt, <i>IBM Microelectronics Division</i> ; John Matthews, <i>TEFEN USA</i>	133
Filling the Technology Gap Through Balanced Joint Development Projects and Contracted Independent Research Providers Scott Runnels, <i>Southwest Research Institute</i> ; Frank Miceli and Bill Easter, <i>Lucent Technologies</i> ; Inki Kim, <i>SpeedFam Corporation</i>	138
Poster Session	
Automated Lot Tracking and Identification System Ulrich Rohrer, <i>SMST Böblingen</i>	142
A Cost Benefit Analysis of Photolithography and Metrology Dedication in a Metrology Constrained Multi-Part Number Fabricator Roger H. Woods, <i>IBM Microelectronics Division</i>	145
Dynamic Capacity Modeling James R. Mercier, <i>IBM Microelectronics Division</i>	148
Effect of 300mm Wafer and Small Lot Size on Final Test Process Efficiency and Cost of LSI Manufacturing System Koji Nakamae, Akihisa Chikamura and Hiromu Fujioka, <i>Osaka University</i>	151
Fab Implementation of a System for Cleaning Wafers Which Survive Wafer-Breakage Events David F. Hilscher, <i>MICRUS</i>	156
A Framework for Real-time Process Control – Part 1: Data Sampling and Processing Graham Rong, Ph.D., <i>GenRad, Inc.</i>	159
Human Based Knowledge for the Probe Failure Pattern Classification with the Use of a Back Propagation Neural Network. Application on Submicron Linear Technologies Carlos Ortega, J. Ignacio, Alonso Montull, Eliseo Sobrino, <i>Lucent Technologies</i>	165
In-line Defect Density Targets for New Technology from Development to Manufacturing Ed Shamble, Mira Ben-Tzur and Shahin Sharifzadeh, <i>Cypress Semiconductor</i>	171
In-Situ Gate Oxide/Electrode Deposition for a 0.5µm BiCMOS Process Flow Tom Carbone, <i>Fairchild Semiconductor</i> ; Gary Solomon, <i>Semitherm Incorporated</i>	174
Manufacturing and Reliability Improvements in Metal-Oxide-Metal Capacitors – MOMCAPs Larry Lowell, <i>Analog Devices, Inc.</i>	181
Manufacturing for Design: Putting Process Control in the Language of the Designer David C. Potts, <i>Fairchild Semiconductor</i>	187
New Business Models for Standard and ASIC Products in the Semiconductor Industry – Competing on Cost and Time-to-Market R. Akella, J. Kleinknecht, J. Gillespie and B. Kim, <i>Stanford University</i> ; A. Frederick, <i>LSI Logic, Inc.</i>	190
Novel Methodology to Include all Measured Extension Values per Defect to Improve Defect Size Distributions Christopher Hess and Larg Weiland, <i>University of Karlsruhe</i>	197
Reducing Perfluorinated Compound Emissions Cynthia Hines, James Pinto, Raymond Izor, Thomas Tamayo and William Miller, <i>IBM Microelectronics Division</i>	203

Keynote Address: Foundry Industry Update, Don Brooks, UMC

†

International Session

Yield Management for Development and Manufacture of Integrated Circuits 208
Hiroshi Koyama and Masayuki Inokuchi, *JEOL Ltd.*

Statistical Methods for Measurement Reduction in Semiconductor Manufacturing 212
Richard Babikian, *Intel Ireland Limited*; Curt Engelhard, *Intel Corp.*

America, Japan and Europe – Which Areas Have the Edge in Customer Satisfaction and Why 216
Christine D. Burgeson, *VLSI Research Inc.*

Contamination Free Manufacturing

Effects of Process Parameters on Particle Formation in SiH₄/N₂O PECVD and WF₆ CVD Processes 221
Z. Wu, S. Nijhawan, S. A. Campbell, N. Rao and P.H. McMurry, *University of Minnesota*

Overcoming the Barriers to Cleaning with Bubble-Free Ozonated De-Ionized Water 226
Timothy Bush, Steven Hardwick and Michael Wikol, *W.L. Gore and Associates, Inc.*

In-Situ Particle Monitoring in a Vertical Poly Furnace 230
Peter Glass and Joe Kudlacik, *IBM Microelectronics Division*; Ray Burghard, *Pacific Scientific Instruments Group*

Advanced Aqueous Wafer Cleaning in Power Semiconductor Device Manufacturing 235
R.S. Ridley, Sr., T. Grebs, J. Trost, R. Webb, M. Schuler, R.F. Longenberger, T. Fenstemacher and M. Caravaggio, *Harris Semiconductor*

Residual Gasses Investigation for Eliminating Contamination In LPCVD Si₃N₄ Process 243
N. Zhang, G. Magloczki, S. Aumick, G. Chiusano, S. Beckett, G. Nicholls and L. Stearns, *MiCRUS*

Advantages to Point of Use Filtration of Photoresists in Reducing Contamination on the Wafer Surface 247
Dennis Capitanio, Ph.D., *Pall Corp.*

Advanced Metrology

Matching Automated CD SEMs in Multiple Manufacturing Environments 252
John Allgair and Dustin Ruehle, *Motorola, Inc.*; John Miller and Richard Elliott, *KLA-Tencor Corp.*

Sidewall Angle Measurements Using CD SEM 259
Bo Su, Tony Pan, Ping Li, Jeff Chinn, *Applied Materials Inc.*; Xuelong Shi and Mircea Dusa, *National Semiconductor Corp.*

Uses of Corona Oxide Silicon (COS) Measurements for Diffusion Process Monitoring and Troubleshooting 262
Richard G. Cosway, Kelvin B. Catmull, Janie Shray, Robert Naujokaitis, Meagan Peters and Don Grant, *Motorola, Inc.*;
Gregory Horner and Brian Letherer, *Keithley Instruments Inc.*

Effective Defect Detection and Classification Methodology Based on Integrated Laser Scanning Inspection and Automatic Defect Classification 266
Yong-Hui Fan, Ph.D. and Yoel Moalem, *KLA-Tencor Corp.*

The Quantitation of Surface Modifications in 200 and 300 mm Wafer Processing with an Automated Contact Angle System 272
Ronald Carpio, *SEMATECH*; David Hudson, *AST Products, Inc.*

Correlation of Ellipsonometric Modeling Results To Observed Grain Structure for OPO Film Stacks 278
Tod E. Robinson, *KLA-Tencor Corp.*

Cost Reduction

Beyond Cost-of-Ownership: A Casual Methodology for Costing Wafer Processing 289
Stephanic Miraglia, Peter Miller, Thomas Richardson, Gregory Blunt and Cathy Blouin, *IBM Microelectronics Division*

A Study in the Continuous Improvement Process: Implementation of an Optimized Scrubber to Replace TEOS Backside Etch Post SOG Etchback 294
W. Au, D. Parks and P. Esquivel, *VLSI Technology, Inc.*

Simulation of Test Wafer Consumption in a Semiconductor Facility 298
Bryce Foster, Doron Meyersdorf, José Padillo and Rafi Brenner, *TEFEN Ltd.*

† Not available at time of printing

Improvement of Silicon Wafer Minority Carrier Lifetime Through the Implementation of a Pre-Thermal Donor Anneal Cleaning Process 303
Larry Martinez, Charley Wang and Tom Hardenburger, *UniSil Corporation*; Nancie Barker and Brian Sohmers, *Siliconix Corporation*

Design for Manufacturability: A Key to Semiconductor Manufacturing Excellence 308
R. Wilcox, T. Forhan, G. Starkey and D. Turner, *IBM Microelectronics Division*

Advanced Processing/Photo & Etch

Highly Selective Oxide to Nitride Etch Processes on BPSG/Nitride/Oxide Structures in a MERIE Etcher 314
W. Graf and G. Skinner, *SIEMENS*, D. Basso, J.M. Martin and E. Sabouret, *IBM France*; F. Gautier, *Applied Materials*

Overview of Plasma Induced Damage After Dry Etch Processing 320
Yuri Karzhavin and Wei Wu, *Motorola, Inc.*

Wet Chemical Cleaning for Damaged Layer Removal Inside the Deep Sub-Micron Contact Hole 327
Mitsuo Miyamoto, *Morita Chemical Industries Co., Ltd.*; Hideto Gotoh, *Texas Instruments, Japan*

Effects of Photoresist Foreshortening on an Advanced Ti/AICu/Ti Metallurgy and W Interconnect Technology (Abstract) 332
C. Whiteside, M. Rutten, H. Trombley, H. Landis and M. Boltz, *IBM Microelectronics Division*

FC2: Off-Axis Focus Control For Critical Level I-Line Photolithography 333
Christopher H. Putnam, Jacek K. Tyminski, Sean J. McNamara, *Nikon Precision Inc.*

Keynote Address: Sub-0.25 micron Interconnection Scaling: Damascene Copper versus Subtractive Aluminum 337
Anthony K. Stamper, Sr. T.L. McDevitt and S. L. Luce, *IBM Microelectronics Division*

Advanced Processing/A New Era of Interconnect Technology

Copper Interconnect - Technology New Paradigms for BEOL Manufacturing 347
Kenneth Rose and Ramon Mangaser, *Rensselaer Polytechnic Institute*

Development of a Production Worthy Copper CMP Process 354
K. Wijekoon, S. Mishra, S. Tsai, K. Puntambekar, M. Chandrachood, F. Redeker, R. Tolles, B. Sun, L. Chen, T. Pan, P. Li, S. Nanjangud, G. Amico, *Applied Materials, Inc.*; J. Hawkins, T. Myers, R. Kistler, V. Brusica, S. Wang, I. Cherian, L. Knowles, C. Schmidt, C. Baker, *Cabot Corporation*

Cu CMP with Orbital Technology. Summary of the Experience 364
Y. Gotkis, D. Schey, S. Alamgir, J. Yang, K. Holland, *Integrated Process Equipment Corporation (IPEC)*

A Study of Post-Chemical-Mechanical Polish Cleaning Strategies 372
C. Huynh, M. Rutten, R. Cheek and H. Linde, *IBM Microelectronics Division*

Process Control and Monitoring with Laser Interferometry Based Endpoint Detection in Chemical Mechanical Planarization 377
David Chan, Bogdan Swedek, Andreas Wiswesser, Manush Birang, *Applied Materials, Inc.*

Factory Automation – WIP Management

A Layer Based Layout Approach for Semiconductor Fabrication Facilities 385
Chao-Fan Chang and Shao-Kung Chang, *Industrial Technology Research Institute*

Quantifying Impact of WIP Delivery on Operator Schedule in Semiconductor Manufacturing Line 391
Allen L. Findley, *IBM Microelectronics Division*

Better Dispatch Application – A Success Story 396
Anke Giegandt and Gary Nicholson, *SIEMENS Microelectronics*

Development and Implementation of an Automated Wafer Transport System 400
Joe Sikich, *Hewlett Packard*

A Focus on Cycle Time vs. Tool Utilization “Paradox” with Material Handling Methodology 405
George W. Horn and William A. Podgurski, *Middlesex General Industries, Inc.*

Advanced Processing - Isolation and Dielectric Issue at 0.18 μ m

A Manufacturable Shallow Trench Isolation Process for 0.18μm and Beyond-Optimization, Stress Reduction and Electrical Performance	413
F. Nouri, O. Laparra, H. Sur, G.C. Tai, D. Pramanik and M. Manley, <i>VLSI Technology, Inc.</i>	
Performance and Productivity Improvements in an Advanced Dielectric Etch Reactor for sub 0.3μm Applications	419
M. Srinivasan, R. Caple, G. Hills, G. Mueller, T. Nguyen, and E. Wagganer, <i>Lam Research Corp.</i>	
A Study of Boron Doping Profile Control for a Low Vt Device Used in the Advanced Low Power, High Speed Mixed Signal IC	423
Alec Chen, Kyle Flessner and Farris Malone, Peyman Sana, Robert Dixon, Peter Ying and Lou Hutter, <i>Texas Instruments, Inc.</i>	
Silicon Nanoelectronics: 100nm Barriers and Potential Solutions	427
Vijay Parihar, R. Singh, K.F. Poole, <i>Clemson University</i>	
On the Integration of Ta₂O₅ as a Gate Dielectric in sub-0.18μm, CMOS Processes	434
T. Devoivre and C. Papadas, <i>ST Microelectronics</i> ; M. Setton, <i>LAM Research</i> ; N. Sandler, <i>Formerly with LAM Research</i> ; L. Vallier, <i>CNET Grenoble</i> ; I. Bouras, <i>Integrated System Development</i>	
Factory Modeling/Simulation	
Batch Size Optimization of a Furnace and Pre-Clean Area By Using Dynamic Simulations	439
H.J.A. Rulkens, E.J.J. van Campen and J. van Herk, <i>Philips Semiconductor</i> ; J.E. Rooda, <i>Eindhoven University of Technology</i>	
Simulation Analysis of 300mm Intrabay Automation Vehicle Capacity Alternatives	445
Gerald T. Mackulak, Ph.D., <i>Arizona State University</i> ; Frederick P. Lawrence and John Rayter, <i>PRI Automation, Inc.</i>	
Management of Multiple-Pass Constraints	451
J. Bonal, A. Sadai, C. Ortega, S. Aparicio, M. Fernandez, R. Oliva, L. Rodriguez, M. Rosendo, A. Sanchez, E. Paule and D. Ojeda, <i>Lucent Technologies</i>	
MOSAIC I Product Transfer Using Virtual Flow Concept	455
Ping Wang, Steve Spivey, Edward Warda, Mark Bowser, Bridgette Cosentino, Ed Zabasajja, Piyush Shah, Salma Imam, John Keller and Joe Fulton, <i>Motorola, Inc.</i>	
Dynamic Dispatch and Graphical Monitoring System	464
Neal Pierce and Tanju Yurtsever, <i>Motorola, Inc.</i>	
BIOGRAPHIES OF SPEAKERS	469
SEMI Publications, Standards, Videos, Network	

Development of a Production Worthy Copper CMP Process

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Abstract

A chemical mechanical polishing (CMP) process for copper damascene has been developed and characterized on a second generation, multiple platen polishing tool. Several formulations of experimental copper slurries containing alumina abrasive particles were evaluated for their selectivity of copper to Ta, TaN and PETEOS film. The extent of copper dishing and oxide erosion of these slurries is investigated with various process parameters such as slurry flow rate, platen speed and wafer pressure. The amount of dishing and erosion is found to be largely dependent on process parameters as well as the slurry composition. It is shown that the extent of oxide erosion and copper dishing can be significantly reduced by using a two slurry copper polish process (one slurry to polish copper and another to polish barrier layers) in conjunction with an optical end-point detection system.

Introduction

The trend in semiconductor industry continues to move towards faster miniaturized integrated circuits for ever increasing device packing densities.¹⁻³ As device architectures are scaled down to submicrometer dimensions, RC delay of metal interconnects plays an important role on the device performance. In order to increase the switching speed, RC delay of metal interconnects must be reduced. Aluminum, interconnects widely used in present VLSI devices, raises reliability concerns with the shrinking device dimensions which rules out the possibility of using Al in future submicron devices. Because of the superior conductivity (resistivity of copper is about 1.7 $\mu\Omega$ -cm compared to 3.0 $\mu\Omega$ -cm for aluminum), higher resistance to electromigration (electromigration limit for copper is 10^7 A/cm² and that for aluminum is 10^6 A/cm²) and reduced susceptibility to joule heating, copper is being

considered as a potential candidate for the replacement of aluminum in future metal interconnects.² However, patterning copper via traditional dry etch techniques is problematic mainly due to lack of volatile copper compound formation at low temperatures. This difficulty can be overcome by following an alternative approach using metal inlay structures such as single and dual damascene in conjunction with chemical mechanical polishing (CMP).⁴⁻⁶

In a Damascene approach, the dielectric layer is patterned and etched using standard procedures. Barrier and copper films are then deposited on the patterned surface. Next, the copper surface topography is removed by CMP. Another challenge in copper technology is developing a good deposition technique for copper. A good barrier layer material is necessary to prevent diffusion of copper into silicon. The barrier layer must be thin to minimize the resistance of contact holes, vias and metal lines. In addition, the barrier layer must be able to be planarized with a CMP process. Materials such as Ta, TaN, and TiN are the most commonly studied barrier layers for copper and are planarized using CMP process. Although many techniques such as sputtering (PVD), chemical vapor deposition (CVD) and electro-chemical deposition (ECD) are currently being considered as film deposition options, further refinements of deposition parameters are necessary in order to obtain more uniform copper films.

Although CMP offers an attractive solution for implementing copper technology in integrated circuits, many challenges exist in developing a manufacturable copper CMP process. The key process issues which must be taken into account in developing a production worthy copper CMP process include control of within-wafer uniformity, wafer-to-wafer uniformity, copper dishing, oxide erosion, corrosion and post CMP

cleaning.⁷⁻¹¹ In view of space limitations, this paper focuses only on the characterization of two key CMP process issues namely copper dishing and oxide erosion. In general, copper dishing is defined as the difference in height between the lowest point of a single copper line/bond pad (usually at the center of the structure) and the surrounding oxide film. Oxide erosion is defined as the difference in the oxide layer thickness within an array of line structures before and after CMP processing (Therefore, the total copper loss of a given feature during CMP is the sum of erosion and dishing).

Both copper dishing and oxide erosion can generate a significant amount of surface non-planarity which cause various process integration problems. They reduce the dielectric spacing and amount of copper in the interconnects, thus leading to increased interconnect resistance and deterioration of device performance. Hence, it is vital to develop a CMP process with minimum copper dishing and oxide erosion. The extent of copper dishing and oxide erosion is found to be heavily dependent on CMP consumables (slurry, pad), process parameters (wafer pressure, platen speed) as well as device features (line width, spacing). In this paper, we describe the reduction of dishing with the use of multiple polishing steps and multiple polishing slurries in conjunction with an optical end-point system.

Experimental Procedures

Copper CMP was carried out on Applied Materials Mirra[®] polisher using Titan[™] polishing heads. The experiments were performed by using polyurethane pads and several experimental copper CMP slurries which use alumina abrasive particles. All slurries were provided by Cabot Corporation. Hydrogen peroxide oxidizer was added to each slurry and mixed well prior to polishing. Slurry was continuously agitated during the experiments. Wafer pressure was varied between 1.0 psi and 6.0 psi, platen speed was varied between 33 rpm to 143 rpm and slurry flow rate was varied between 75 ml/min and 220 ml/min. In every case the end-point was detected with the ISRM[™] system. The Laser based ISRM module is embedded in the polishing platen. When the laser beam is incident on the film surface during polishing, the ISRM system probes the film surface, collects and processes data, and displays a real time signal. This process continues until a pre-set end point is reached. Data are collected only when the laser beam is incident on the film surface, therefore, the ISRM signal does not depend on process parameters such as platen

velocity, down force, slurry flow rate or pad hardness.

The wafers used in this study contained test structures with different line widths and spacings. Copper deposition was carried out with either PVD, CVD and/or ECD techniques. The barrier layers were either Ta or TaN. In the case of a single slurry process the same slurry was used to polish copper and barrier layers. In the case of two-step copper polish process, one slurry was used to polish copper and the other slurry was used to polish the remaining barrier layers. Copper polishing was carried out on the first platen and the barrier layer was polished on the second platen. The buff and rinse step was accomplished on the third platen. In both cases, multiple polishing steps were used. During some of the single slurry processes, one or more polishing steps were carried out on the first platen and the rest of the steps were carried out on the second platen. Again one buff and rinse step was done on the third platen. All the erosion and dishing measurements were performed with a Tencor HRP200 high resolution profilometer.

Results and Discussion

The main contribution to copper dishing and oxide erosion comes from over-polishing, which is often necessary to assure complete removal of copper and barrier residues across the entire wafer. The uniformity variations of the copper thickness of the as deposited wafers can make the CMP step problematic. In the ideal case, one would like to fully planarize the copper layer before reaching the barrier layers. Depending on the slurry chemistry, the same slurry or a different slurry can be used to polish residual copper and the barrier layers thus creating a structure with metal inlaid in dielectric. Large differences in chemical reactivity of copper and tantalum result in dissimilar polishing rates of the two layers. In the case of single slurry processing, the barrier removal rate is significantly lower than that of copper. Hence, during barrier polishing, the exposed copper feature dishes due to continued chemical and mechanical action. Table I shows the copper removal rates and selectivities of copper to barrier layers for the slurries used in this study.

	Slurry A	Slurry B	Slurry C
Cu Removal Rate ($\text{\AA}/\text{min}$)	7500	5900	169
Cu:Ta selectivity	47:1	30:1	~ 1:1
Cu:TaN selectivity	19:1	11:1	~ 1:2
Cu:PETEOS selectivity	137:1	207:1	~ 3:1

Table I. Copper removal rate and selectivity to barrier films for various copper CMP slurries at a platen speed of 43 rpm and a wafer pressure of 4.0 psi.

As shown in Table I, either slurry A or B can be used in the single slurry process since they have a high copper removal rate. Slurry C is well suited for clearing barrier layers since the copper removal rate in this slurry is comparable to barrier removal rates. An ideal single step slurry would polish Cu and the barrier film at similar removal rates (low selectivity to barrier) and would also have a very low removal rate for the field oxide (high selectivity to SiO_2). Additionally, such an ideal slurry would remove

residual Cu and barrier without dishing Cu interconnects and eroding the dielectric layer.

The majority of the single slurry process discussed in the present work was carried out with slurry A. The dependence of the copper dishing and oxide erosion on the process parameters such as slurry flow rate, platen speed and wafer pressure was investigated with this slurry. In every case, end-point was detected with the ISRM system. All wafers were 10% over-polished after the end-point was detected. Figure 1 shows a end-point trace of a blanket copper film containing Ta barrier film.

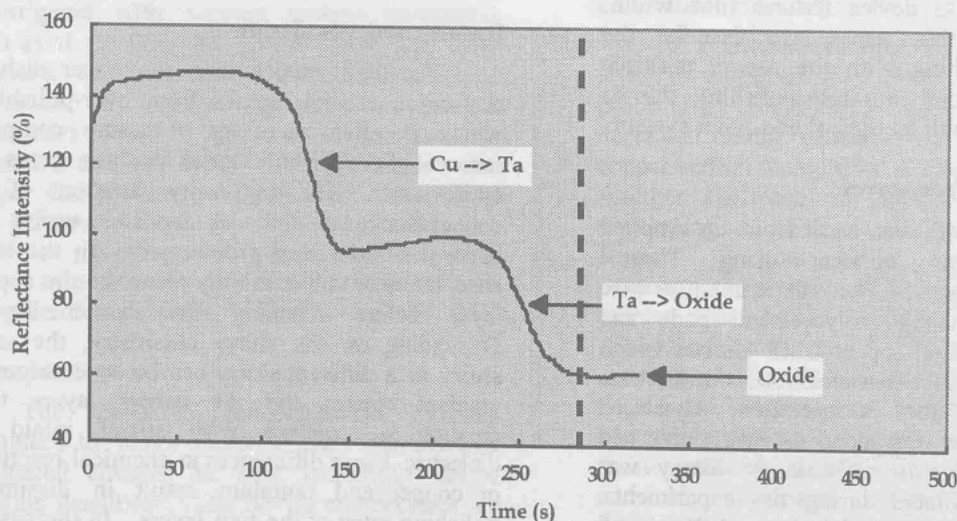


Figure 1. ISRM trace of a blanket copper film containing Ta barrier. End-point is shown by the dotted line.

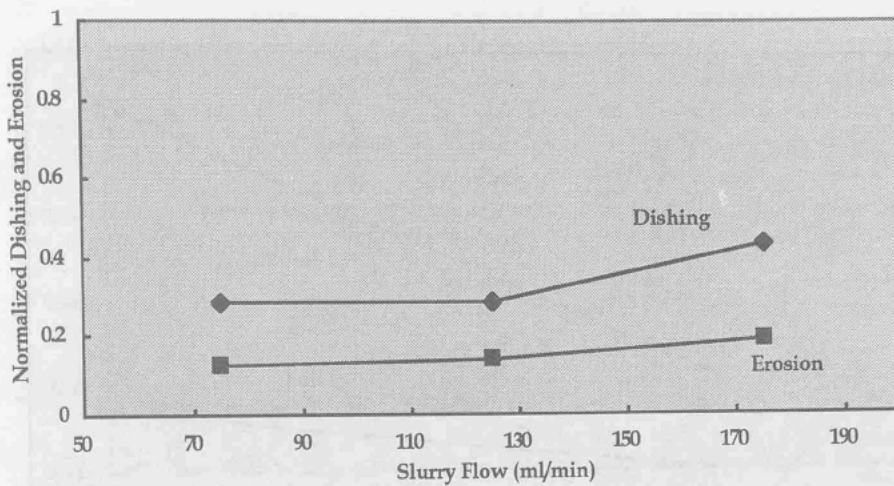


Figure 2. Dependence of copper dishing and oxide erosion on slurry (slurry A) flow rate. Platen speed and wafer pressure were held constant. Dishing was measured on a 50mm thick line (pitch 150mm) while erosion was measured at a 0.5mm thick line (pitch 1.0mm).

As shown in Figure 1, different interfaces of the film stack can be accurately detected with the end-point system. The amount of over-polish in a single slurry process is defined as the percent polish time after the end-

point is reached. Figures 2-4 show the extent of copper dishing observed in a 50 μ m copper line and extent of oxide erosion observed in a 0.5 μ m feature as process parameters such as slurry flow rate, wafer pressure and platen speed are varied.

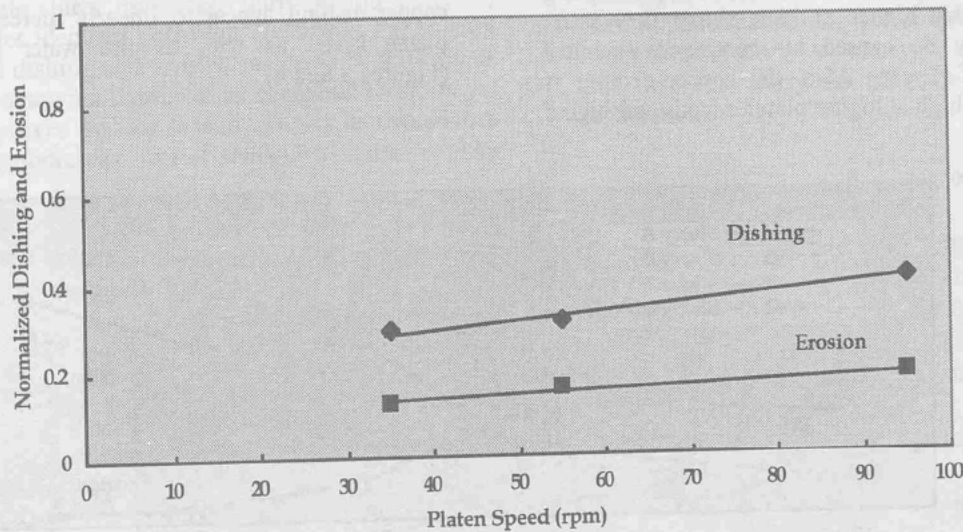


Figure 3. Dependence of copper dishing and oxide erosion on platen speed (slurry A). Slurry flow rate and wafer pressure were kept constant. Dishing was measured on a 50mm feature (pitch 150mm) while erosion was measured at 0.5mm line (pitch 1.0mm).

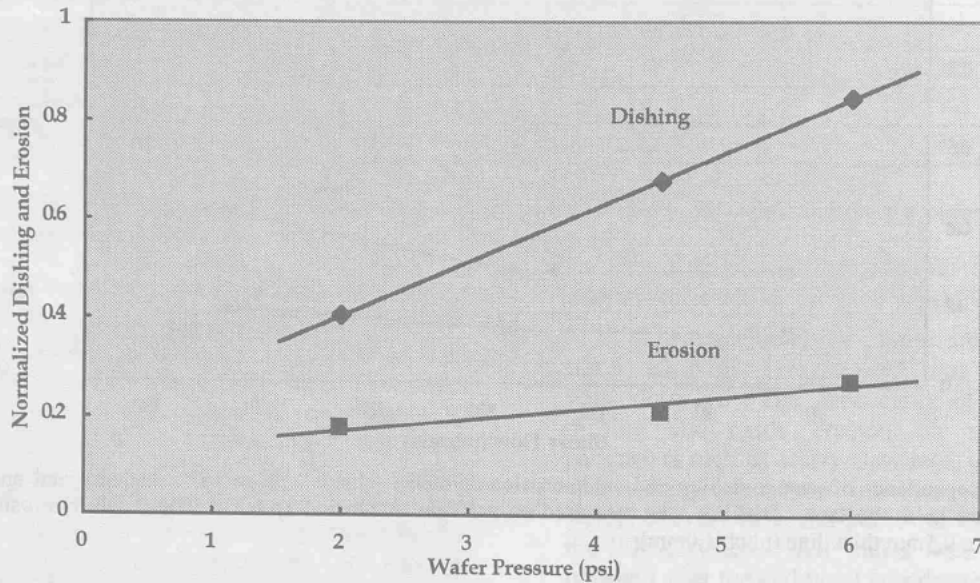


Figure 4. Dependence of copper dishing and oxide erosion on wafer pressure (slurry A). Platen speed and slurry flow rate were held constant. Dishing was measured on 50mm feature (pitch 150mm) while erosion was measured at 0.5mm line (pitch 1.0mm).

Data in Figure 2 show that copper dishing is somewhat higher at high slurry flow rates. This may be caused by continued chemical etching of copper. Also, the copper dishing is relatively high at higher platen speeds and higher

wafer pressures. Both the oxide erosion and copper dishing appear to linearly increase with platen speed as well as the wafer pressure (Figures 3 and 4).

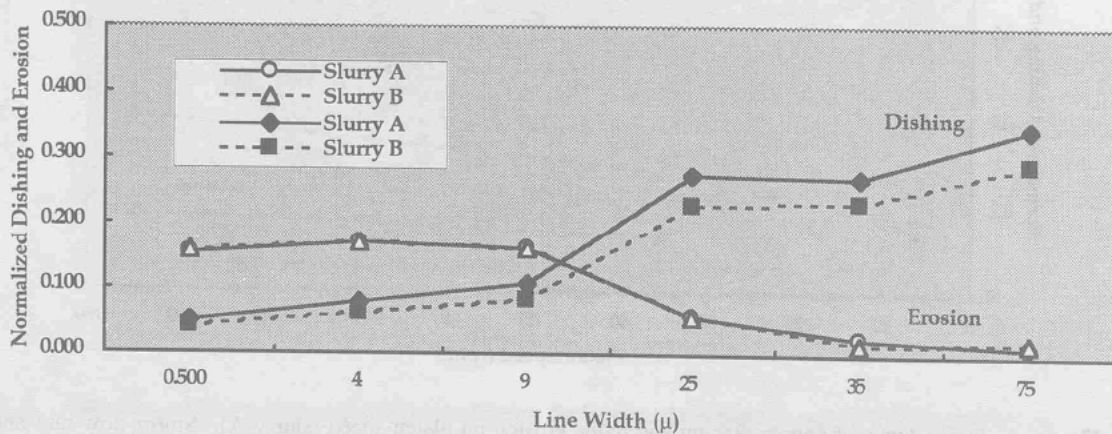


Figure 5. Comparison of copper dishing and oxide erosion of single slurry process under identical experimental conditions (slurry A and slurry B). Copper dishing on slurry B is relatively smaller compared to that of slurry A. Both slurries have similar oxide erosion performance.

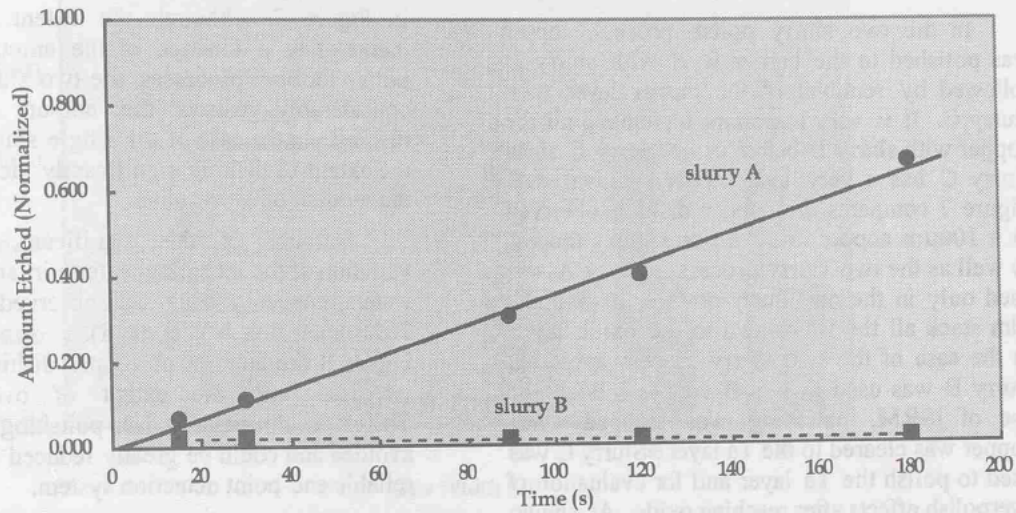


Figure 6. Static copper etch rate at room temperature (slurry A and Slurry B).

In order to improve the dishing in a single slurry process, another slurry formulation (slurry B) was evaluated. Figure 5 compares the extent of dishing and erosion observed with single slurry processes (slurry A and slurry B) under identical polishing conditions. It is seen that dishing and erosion performance of slurry B is somewhat improved as compared to slurry A. Improved dishing in slurry B may be related to a low static etch rate of slurry B (Figure 6). As

shown in Figure 6, static copper etch rate of slurry A is considerably higher than that of slurry B. Therefore, slurry B reduces static etching during the barrier removal and over-polish, leading to lower copper dishing levels. Because of the improved dishing performance of slurry B (compared to slurry A), slurry B was selected as the first step slurry for the two-slurry process evaluations.

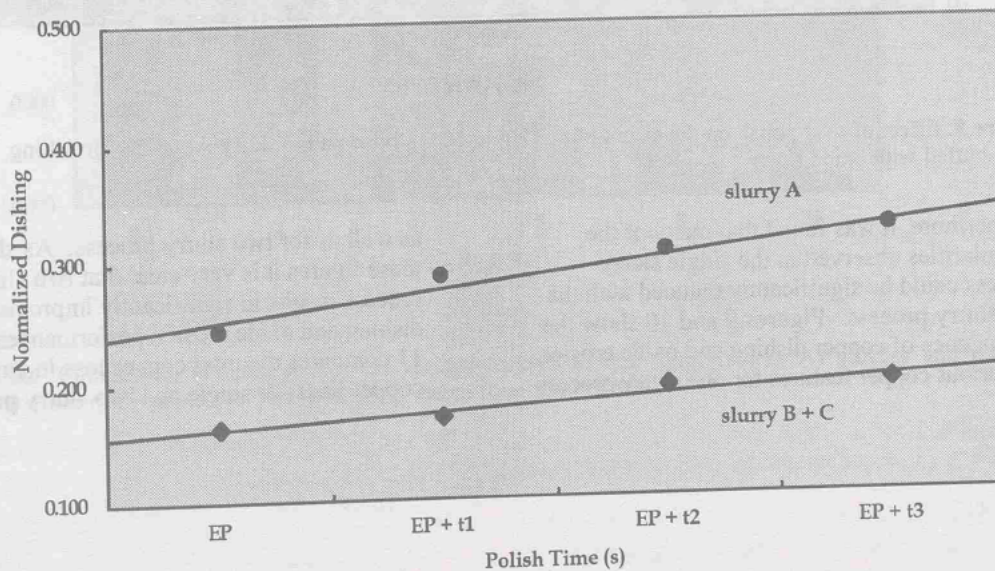


Figure 7. Comparison of copper dishing of 100 mm bond pad for one slurry (slurry A) process and two slurry (slurry B and slurry C) processes. In the case of one slurry process, EP is the time to reach end-point and t1, t2, t3 are the over polish times. In the case of the two slurry process, t1, t2, and t3 are the over polish times with slurry C.

In the two slurry polish process, copper was polished to the barrier layer with slurry B followed by removal of the barrier layer with slurry C. It is very important to remove all the copper with slurry B before using slurry C since slurry C has a very low copper removal rate. Figure 7 compares the copper dishing observed in a 100 μ m copper line with one slurry process as well as the two slurry process. Slurry A was used only in the one slurry process to clear the film stack all the way down to the oxide layer. In the case of the two slurry process approach, slurry B was used to polish copper. With the use of ISRM, polishing was stopped when copper was cleared to the Ta layer. Slurry C was used to polish the Ta layer and for evaluation of overpolish effects after reaching oxide. As shown

in Figure 7, although the extent of dishing increases as a function of the amount of over polish for both processes, the two slurry process considerably reduces the amount of copper dishing. In the case of the single slurry process, the extent of dishing significantly increases with the amount of over-polish.

Because of the significant uniformity variation of the incoming wafers, in some copper wafers, copper dishing was observed even at a 20% under-polish (Figure 8). As shown in Figure 8 the amount of copper dishing linearly increases with the extent of over polish. Therefore, unnecessary over-polishing should be avoided and could be greatly reduced by using a reliable end-point detection system.

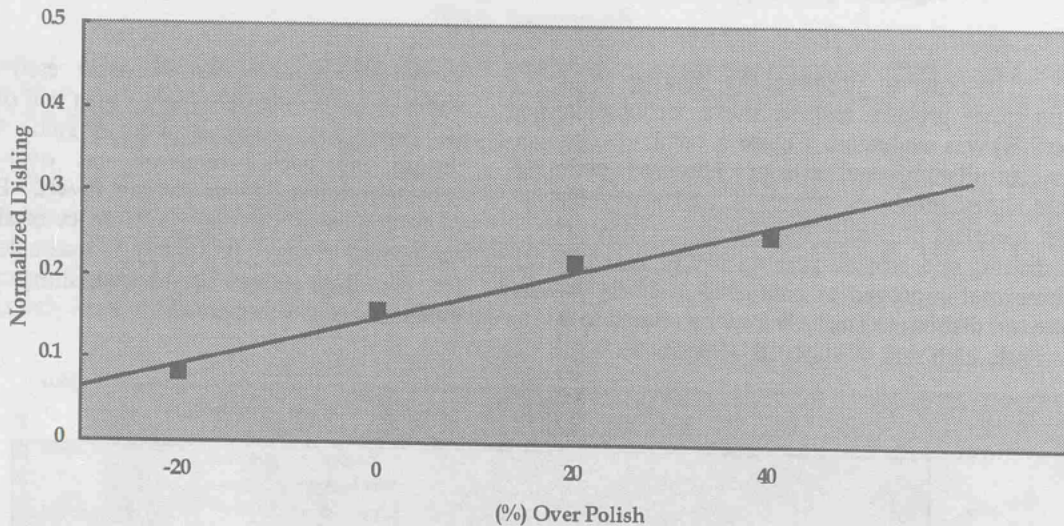


Figure 8. Effect of over polish on the extent of dishing in 100 m bond pads (slurry A). After polishing the wafers were buffed with oxide slurry.

Furthermore, it was found that many of the irregularities observed in the single slurry process could be significantly reduced with the two slurry process. Figures 9 and 10 show the dependence of copper dishing and oxide erosion on various copper features for one slurry process

as well as for two slurry process. As shown in these figures it is very clear that two slurry process results in significantly improved copper dishing and oxide erosion performances. Figure 11 compares the total copper loss in various copper lines for single and two slurry processes.

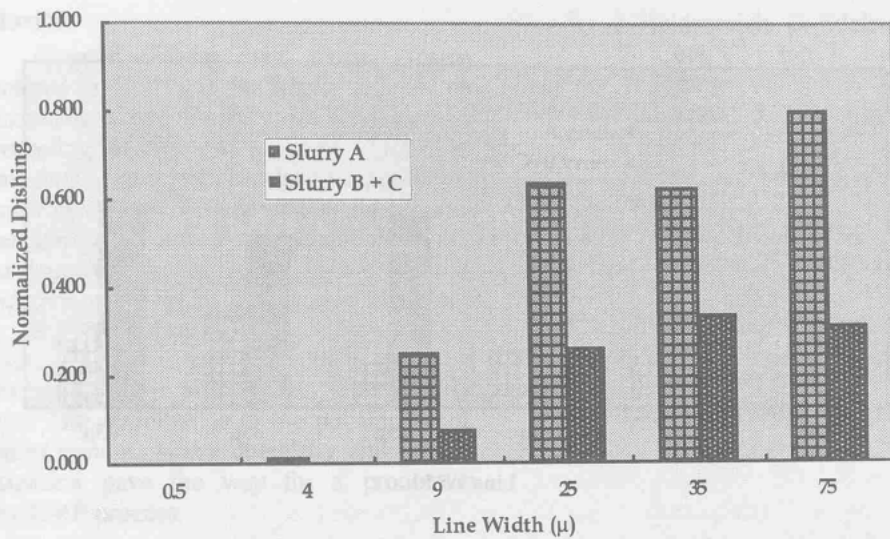


Figure 9. Comparison of copper dishing of various copper features for one slurry (slurry A) process and two slurry (slurry B + slurry C) processes.

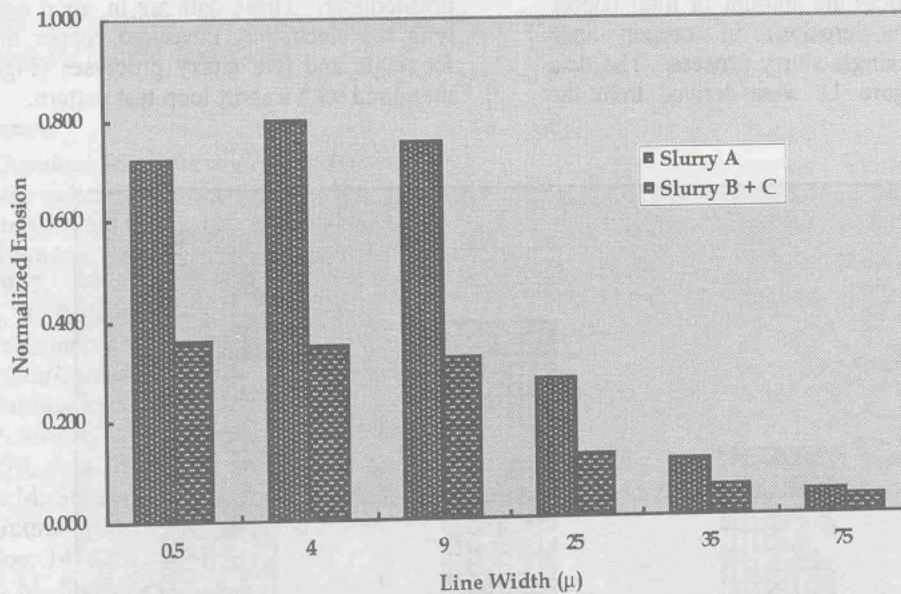


Figure 10. Comparison of oxide erosion on various features for one slurry (slurry A) process and two slurry (slurry B + slurry C) processes. Pattern density varies from 55% to 80%.

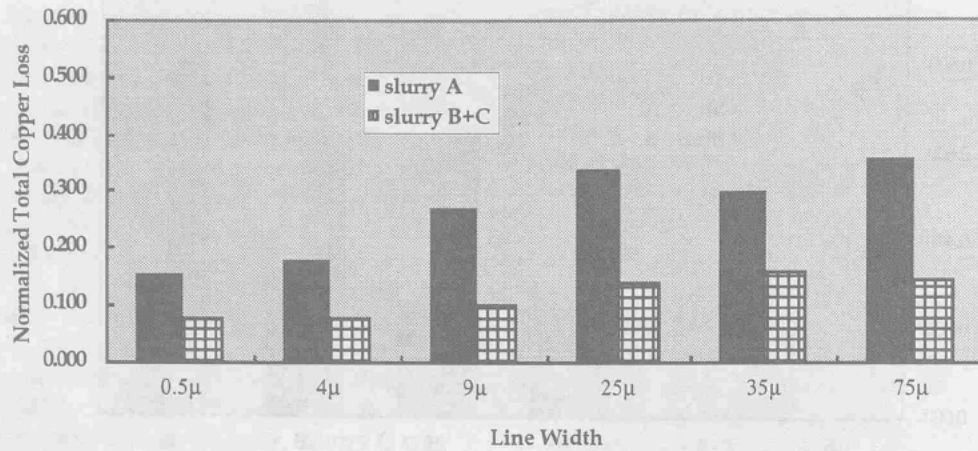


Figure 11. Comparison of total copper loss (dishing + erosion) for one slurry (slurry A) and two slurry (slurry B + slurry C) processes in a variety of copper line sizes.

As seen in Figure 11, the two slurry process significantly reduces the amount of total copper loss (dishing + erosion) in copper lines compared to the single slurry process. The data presented in Figure 11 were derived from the

measurements made with a high resolution profilometer. These data are in good agreement with the electrically measured copper thickness for single and two slurry processes (Figure 12) measured with a short loop test pattern.

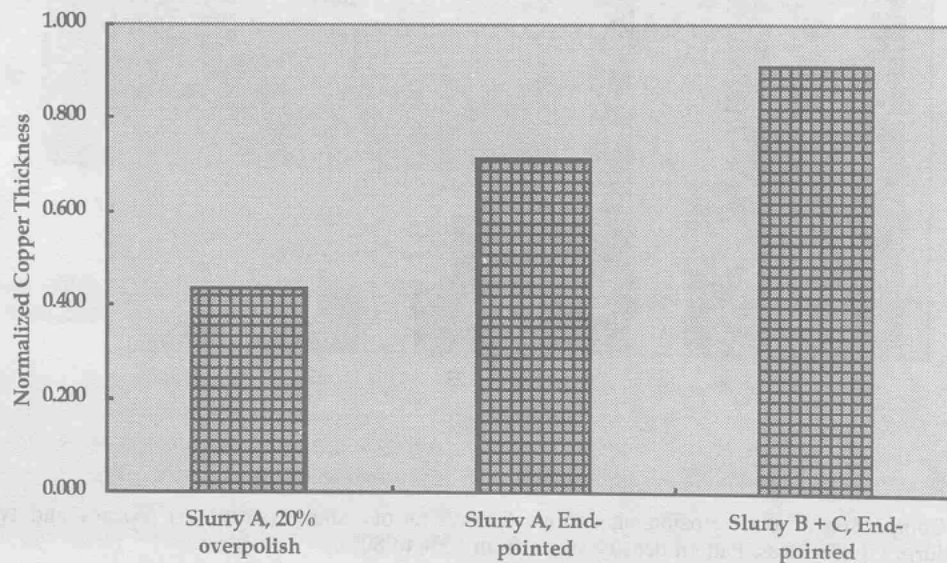


Figure 12. Comparison of electrically measured copper thickness for one slurry (slurry A) and two slurry (slurry B + slurry C) processes. Measurements were performed on a 10 m x10m Van der Pauw structure.

The data displayed in Figure 12 were measured on 10μx10μ Van der Pauw structures. As expected, the wafers processed with slurry A show heavy copper loss in the line structures. It can be seen that about 40% of additional copper is lost by performing 20% over-polish after end-point detection. However, in the case of two slurry process, only 10% copper is lost when polishing was stopped at end-point.

Conclusion

Copper dishing and oxide erosion encountered in CMP can be largely reduced by implementing a two slurry process as well as implementing multiple process steps. Use of an accurate end-point system can lead to substantial reduction in copper dishing and oxide erosion. Further improvements to slurry chemistry and copper deposition techniques are highly desirable for improving the extent of copper dishing and oxide erosion observed in current CMP processes. Also, the use of multiple polishing platens greatly simplifies two slurry CMP process. The combination of the polishing tool, end-point system, slurry chemistry and process optimization pave the way for a production worthy CMP process.

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